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BUREAU OF SOILS—BULLETIN No. 50.

MILTON WHITNEY, Chief.

MOISTURE CONTENT AND PHYSICAL CONDITION OF SOILS.

BY

FRANK K. CAMERON AND FRANCIS E. GALLAGHER.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1908.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., September 13, 1907.

Sir: I have the honor to transmit herewith the manuscript of a technical article entitled Moisture Content and Physical Condition in Soils. In accordance with your suggestion, it has been submitted to Assistant Secretary Hays, who concurs with me in recommending it for publication.

Respectfully,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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CONTENTS.

Page.

Introduction 7

Penetration and cohesion 10

  Previous work 10

  Relation of penetration to moisture content 17

    Object of experiments 17

    Experimental methods 18

    Results for Podunk fine sandy loam 19

    Results for Miami black clay loam 24

    Results for Leonardtown loam 25

    Results for Muck 26

Apparent specific gravity or volume 27

  Previous work 27

  Relation of volume to moisture content 29

    Object of experiments 29

    Experimental methods 30

    Results for Podunk fine sandy loam 31

    Results for Miami black clay loam 35

    Results for Leonardtown loam 36

    Results for Muck 38

  Successive wetting and drying 40

    Object of experiments 40

    Experimental methods 40

    Results for Miami black clay loam 41

    Results for Muck 43

Rate of evaporation 45

  Relation of rate of evaporation to moisture content 45

    Experimental methods 45

    Results for Podunk fine sandy loam 46

    Results for Miami black clay loam 47

    Results for Leonardtown loam 47

    Results for Muck 48

Moisture distribution 49

  Moisture films 49

  Effect of moisture distribution on volume change 50

  Effect of moisture distribution on penetration 51

  Effect of moisture distribution on rate of evaporation 53

  Critical moisture content and moisture equivalent 54

  Optimum water content as regards plant growth 57

Apparatus and methods 59

  Screening apparatus 59

  Packing apparatus 61

  Penetration apparatus 63

  Apparatus for measuring volume 65

    Preliminary method 65

    Soil column method 67

    Micrometer method 68

    Cathetometer method 69

ILLUSTRATIONS.

Page.

FIG. 1. Influence of size of soil particles on penetration-moisture results for calcareous sand and for quartz, according to Puchner 14
2. Penetration-moisture results for different soil components and mixtures of them, according to Puchner 16
3. Penetration-moisture results for Podunk fine sandy loam 20
4. Penetration-moisture results for Podunk fine sandy loam by method of Puchner and by method of loose packing 22
5. Penetration-moisture results with different packings 23
6. Penetration-moisture results for Miami black clay loam 24
7. Penetration-moisture results for Leonardtown loam 25
8. Penetration-moisture and apparent-specific-gravity-moisture results for Muck 26
9. Apparent-specific-gravity-moisture results for Podunk fine sandy loam 32
10. Apparent-specific-gravity-moisture results for Podunk fine sandy loam with different packings 32
11. Volume-moisture results for Podunk fine sandy loam by the micrometer method 34
12. Volume-moisture results for Podunk fine sandy loam by the cathetometer method 34
13. Volume-moisture results for Miami black clay loam by the soil column method 35
14. Volume-moisture results for Miami black clay loam by the cathetometer method 36
15. Apparent-specific-gravity-moisture results for Miami black clay loam 36
16. Volume-moisture results for Leonardtown loam by the micrometer method 37
17. Volume-moisture results for Leonardtown loam by the soil column method 38
18. Apparent-specific-gravity-moisture results for Leonardtown loam 39
19. Volume-moisture results for Muck by the soil column method 39
20. Volume-moisture results for Muck by the cathetometer method 40
21. Volume changes with successive wetting and drying of loosely packed Miami black clay loam 42
22. Volume changes with successive wetting and drying of closely packed Muck 43
23. Rate-of-evaporation-moisture results for Podunk fine sandy loam 46
24. Rate-of-evaporation-moisture results for Miami black clay loam 46
25. Rate-of-evaporation-moisture results for Leonardtown loam 47
26. Rate-of-evaporation-moisture results for Muck 48
27. Apparatus for screening soils 60
28. Apparatus for packing soils 62
29. Penetration-packing results 63
30. Apparatus for measuring penetration 64
31. Apparatus for glass tube method of measuring changes in soil volumes 65
32. Apparatus for soil column method of measuring changes in soil volumes 66
33. Apparatus for micrometer method of measuring changes in soil volumes 68

MOISTURE CONTENT AND PHYSICAL CONDITION OF SOILS.

INTRODUCTION.

It is generally recognized that the physical properties of a soil determining crop adaptation and growth are moisture supply, aeration, temperature, texture and structure, and "physical condition." Under these heads fall practically all physical investigations on the soil. Of course "physical condition" is by far the most important in practice, because it is the one factor directly under the control of the agriculturist, such control of the others as may be possible being usually but incidental to control of the last. Everyone who has had any experience can judge with comparative readiness as to whether a soil is in good or poor physical condition. But apparently no two observers will agree entirely as to the basis of their judgments. It is said that a soil in good physical condition must be loose, friable, loamy, have a crumb structure, work well, have a "live" look, etc., properties which are sufficiently definite to be recognized readily, but which are not susceptible of exact measurement and quantitative expression. It is evident that a comparison of soils as to their physical condition is mainly a matter of individual judgment, subject to the limitations and errors of a personal equation; and while physical condition is the most readily under practical control, paradoxical as it may seem, it is the most difficult of soil properties to study. This is because the concept or idea of "physical condition" is a summation of a number of properties rather than any one property, and because no satisfactory method of measuring this sum has yet been devised. Nevertheless, much can be done to advance our knowledge of this important subject by studies in the field and, especially, in the laboratory.

In the present bulletin are given the results of an investigation on the relation of physical condition to moisture content, in which the soils were put into different states with different amounts of water present and then subjected to various physical tests yielding measurable results. In this work the judgment of several experienced greenhouse men was available for determining the physical condition of the samples before and after the several measurements were made. It has been found that the physical condition of the soil is connected in the most intimate way with its water content. Not only is this true of its general behavior and appearance, its "workability," etc., but systematic quantitative measurements on penetrability, volume changes, apparent specific gravity, and rate of evaporation showed a direct dependence on the water content. All these properties varied regularly with regular change in the water content when the sample was in the best possible physical condition obtainable with any given water content.

One particular water content has been given special consideration. It is perfectly well known to agriculturists generally and greenhouse men especially that there is a particular water content (or perhaps a more or less narrow range of water content) differing with each soil at which plants grow best, other conditions being the same. This is popularly known as the "optimum" water content, and is supposed to be that content from which plants draw most readily their needed supply; in other words, the optimum water content is supposed to be determined by the physiological necessities of the plant rather than by the physical properties of the soil. There are difficulties, however, for which this view fails to offer sufficient and satisfactory explanation. Plants can do quite well in soils containing considerably less than the optimum water content, other conditions being favorable. That is to say, there is no decided or sharp falling off in the plant growth corresponding with a lowering of the water content until the drought limit is approached, a limit generally much below the "optimum;" and, on the other hand, there is no especial difficulty in carrying some of our common crops to a satisfactory maturity in water cultures. The investigation described in the following pages shows conclusively not only that physical condition and the several properties on which it depends have an intimate relation with the water content of the soil, but that there is marked accentuation in these properties at a critical water content; and that this critical content is identical with the optimum water content. The *moisture-penetration* curve shows a minimum force required for penetration at the optimum water content; the *moisture-apparent specific gravity* curve shows a minimum point at the optimum water content; the curves for *evaporation* show a marked difference in the rate of evaporation above and below the optimum water content. It is apparent, therefore, that the true significance of optimum water content is that particular content at which the soil can be put into the best possible condition for plant growth. The plant can then best draw its needed water from the soil because all the other factors making for good growth are also at their best. Moreover, an increase in water content in excess of the optimum generally produces a greater detrimental effect on the plant than a decrease below the optimum.

Furthermore, it should be borne in mind that practical men in bringing a soil to optimum water content judge when this point is reached by the appearance and "feel" of the soil; i. e., by the physical condition into which it can be brought, and not directly by any plant phenomenon. There is a widespread impression that the optimum water content for any one soil varies for different plants. That is, the *physiological* optimum, as determined by the plant, may not coincide with the *physical* optimum, as determined by the soil properties. While this may be true for certain exceptional cases, it is erroneous as regards the majority of common field crops, since the water content that makes for the best physical condition of the soil is as a necessary consequence the best for plant growth. Other evidence from experiments on wilting will be given in detail in support of this view. The available evidence seems to be conclusive that the problem of water supply and optimum water content is fundamentally a soil problem and incidentally a plant problem.

Another point which this investigation has brought out in a striking way is the "hysteresis" observable in the volume change when a soil is alternately wetted and dried out. This process results in a natural packing of the soil and is seriously detrimental to the maintenance of good tilth if the extremes of moisture content reached are wide apart. The causes for and mechanism of this process have been made clear by the experiments here recorded.

The importance in general farming of having a proper moisture content in the soil before plowing or other cultural operations is well known, although not always so well observed. It is regrettably common to find cases where the soil has been worked while too dry, and even more so are the cases where a soil has been worked while too wet, entailing disastrous results, requiring even years for rectification. These latter are the most baffling cases which the soil expert encounters.

The usual practice in irrigation gardening and greenhouse work of adding an excessive amount of water, so as to be on the "safe side," is far from the ideal soil management, and the working out of a better and at the same time an economical system of maintaining the water content constant, or approximately so, should be the aim of practical workers in these fields. It is believed that the data brought out in this bulletin will be of material assistance in understanding the phenomena involved in these difficult practical problems and in devising methods for the treatment and amelioration of lands which have been improperly handled.

In the course of this investigation a number of special methods and forms of apparatus were devised which it is believed will have a value not only for future investigation, but as a desirable part of the equipment of a laboratory for student work. It has been deemed well, therefore, to give quite complete and detailed descriptions, and to this end the methods and apparatus are described and illustrated in a special chapter at the end of the bulletin, and only brief references to them are given in the text describing the investigations.

PENETRATION AND COHESION.

PREVIOUS WORK.

A property of the soil of recognized agricultural importance is *cohesion*, or the force with which the soil particles cling one to another. The previous work on penetration has been usually incidental to investigations of cohesion. This property has been studied because it is a determining factor of the ease of tillage and because it gives a measure of the physical condition of the soil and its variation under different treatments. In these studies two methods have been employed. In the one the crushing strength of cylinders of soil has been taken as a measure of the binding together, or cohesion, of the soil particles; in the other the "firmness" of the soil, which is due to its cohesion, has been determined by the resistance offered to the introduction of a sharp instrument. These latter investigations have been regarded of especial value in showing the relative resistance of different types of soils to tillage and root penetration.

Volker [a] applied the penetration method to actual measurements in the field, without, however, obtaining definite results. A penetration method was used by Meyer [b] in which four pegs fastened to the corners of a square were forced a definite distance into the soil by weights placed on the square surface. The crushing method was used in an investigation by Schübler,[c] who molded damp samples of soil into rectangular prisms. The samples were then either allowed to dry in the form or were removed while still damp and dried in the air or at a high temperature. The apparatus used to determine the crushing strength of the samples consisted of a beam supported on a fulcrum about one-third the distance from one end. On the long arm of this lever was hung a scale pan to which weights could be added gradually. At the opposite end of the beam was a counterpoise that balanced the scale pan and beam. On the long arm, a short distance from the fulcrum, a blade was fastened, free to move in the vertical plane of the beam. The dried soil sample was placed under this blade and weights added to the scale pan until the soil was either cut or crushed by the knife. The weight added was taken to represent the cohesion of the soil. The highest absolute cohesion value, that for pure clay, was taken as 100 and the other measurements compared with this. The series of relative values obtained for the different soils is shown in Table I.

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[a] Neue Moglinische Annalen der Landwirtschaft, 4, 119 (1818); ref. in Puchner, Forsch. auf dem Geb. Agr.-Phys., 12, 196 (1889).

[b] Anlage zur Flora des Königreichs Hannover (Göttingen), 307 (1822).

[c] Grundsätze der Agrikulturchemie, Leipzig, 2, 74 (1838).

TABLE I.—*Cohesion of dry soils, according to Schübler.*

Soil.	Cohesion of dry soil compared to clay.	Soil.	Cohesion of dry soil compared to clay.
Pure clay (kaolin)	100.0	Humus	8.7
Clay soil	83.3	Garden soil	7.6
Fertile clay	68.6	Gypsum	7.3
Barren clay	57.3	Calcareous soil	5.0
Hofwyl soil	33.0	Calcareous sand	.0
Jura soil	22.0	Quartz sand	.0

This table shows that clay in the dry form has a relatively high cohesion, while humus and lime soils are low, and sand does not bind together at all. By comparing some of the values obtained for the above soils with their mechanical analyses it was shown that in the clay soils the presence of humus or sand greatly reduces the cohesion.

This method is of interest in showing the binding qualities of very dry soils, yet it is open to the objection that the results obtained by it do not give reliable data for soils under ordinary cultural conditions. It is rare for field soils to dry out to an extent comparable with the condition reached in this method; and it will be pointed out later that the relative values for the cohesion of different soils vary with the quantity of water present. The table shows further that the cohesion value of sand is zero, which means that in drying out the sand samples did not retain their form. If the measurements are to give a basis of comparison for the ease of working the soils in the field, such a value is of course meaningless. A method which depends on an unsupported soil column is evidently too wide a departure from field conditions.

It is apparent that measurements of soil cohesion are not of great agricultural interest unless they take into account the variable quantity of water in a soil at different times, since this quantity plays a most important rôle in determining all of its physical properties. Extensive experiments in soil cohesion taking account of this factor were made by Haberlandt,[a] in which he measured cohesion by the crushing strength of cylinders. He also divided some of his soil samples into three fractions, depending on the size of the grains, and in this way he was able to study the relation between soil cohesion and size of the particles. In the method as first used by him he molded cylinders of the soil in a glass tube one end of which was covered by a thin cloth. The cylinders and the glass tube were dipped in water to the depth of 1 centimeter and the soil allowed to take up moisture freely. The soil column, when removed from the glass tube, was 2 centimeters in diameter and 3 centimeters high. The cylinder was then allowed to dry until it had attained the desired moisture content, when the crushing strength was determined by placing a glass vessel on the top of the column and pouring in water until the soil gave way. From the weight of the vessel and water the value for the crushing strength was obtained in grams. The results for one soil are given in Table II.

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[a] Wissenschaftlich praktische Untersuchungen auf dem Gebiete des Pflanzenbaues, Wien, 1875, Vol. I, p. 22.

TABLE II.—*Moisture-cohesion relations, according to Haberlandt.*

Grade of particles.	Moisture content.	Weight required to break down soil cylinders.
	Per cent.	*Grams.*
Coarse	32.6	120
	19.8	320
	13.1	725
	7.7	290
	2.4	170
Medium	25.9	225
	19.2	265
	16.8	500
	3.1	1,115
	1.2	1,080
Fine	33.4	450
	25.8	1,150
	7.0	1,900
	4.2	2,400
	1.9	4,200

From Table II it will be seen that the strength with which the particles are held together is greatly dependent on the moisture content of the soil. In two of the samples the cohesion value reached a maximum, indicating that in these soils a certain water content was of particular significance in regard to the cohesion. The soil with the finest particles became bound together more closely as it dried out, which is in agreement with the results of other investigators.

In another experiment Haberlandt studied the effect of mixing various quantities of sand and of moor soil with the sample of soil which was used in the previous experiment. As the percentage of sand increased the resistance to crushing diminished. This was likewise true of mixtures of the same soil with the moor soil.

In a later investigation Haberlandt[a] molded cylinders of the soil in a glass tube in the same way as before, and in addition to determining the crushing strength he measured the resistance to breaking under a transverse load, by placing the soil cylinder across two parallel horizontal supports 6 centimeters apart. Midway between the supports a scale pan was suspended from the soil cylinder, and weights were added continually until the soil column gave way. The weight required was taken as a measure of the "absolute" firmness of the soil. The pieces of the broken soil column were cut down to the desired size and a measurement of the "relative" firmness was made by crushing the sample in the same manner as before described. Measurements were made on twelve different soils in which the values for "absolute" firmness varied from 115 to 3.5 and for "relative" firmness from 9,000 to 700. Compared by either method the soils fell in practically the same order.

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[a] Forsch. auf dem Geb. Agr.-Phys., 1, 148 (1878).

The investigation was further extended by Haberlandt to determine the change in cohesion upon the addition of small amounts of charcoal and lime. The results are given in Table III.

TABLE III.—*Effect of lime and charcoal on cohesion, according to Haberlandt.*

Mixture.	Cohesion.
	Kilograms.
Untreated soil	31.4
Soil with 1 per cent charcoal	20.0
Soil with 1 per cent lime	8.9

The cohesion was reduced 36 per cent by charcoal and 72 per cent by lime. From his various experiments Haberlandt concluded: (1) The cohesion of different soils is widely different; (2) the cohesion depends on the size of the particles; (3) the cohesion of the soil is greatly diminished by the addition of lime, and this has a great influence in determining the ease with which soils can be worked in the field; (4) at some moisture content the cohesion is least for every soil. This last conclusion Haberlandt considered of great importance as bearing upon the question of the ease of working the soil in the field.

An extensive and valuable contribution to the literature of soil cohesion and penetration was made by Puchner,[a] who obtained values for "absolute" and "relative" firmness, both by the method of penetration and by a method similar to that of Haberlandt. The apparatus by which Puchner measured the penetration of soils consisted of a vertical shaft running through a metal guide. On the lower end of the shaft was fastened a penetrating knife blade 2 centimeters broad and 1 centimeter high, the angle of the cutting edge being 13°. The upper end of the shaft carried a scale pan to which weights were added directly until the blade was forced a required depth into the soil. The unloaded shaft and scale pan were counterpoised by a weight running over a pulley. By means of a pestle the dry soil sample was packed into a dish having a perforated bottom to permit of saturation with water taken up by capillarity. This amount of water was taken to represent the total water capacity of the soil, or 100 per cent moisture content. The samples were then allowed to dry until they reached the moisture content desired, when the penetration was measured by the apparatus just described.

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[a] Forsch. auf dem Geb. Agr.-Phys., 12, 195 (1889).

The influence of changing moisture content and that of size of particles on penetration were studied. For this purpose he used quartz sand separated into seven divisions, varying from 0.01 millimeter to 2 millimeters in diameter. The cohesion of these seven samples and a sample composed of all sizes was measured with varying water content. Experiments were also made on a calcareous soil (Kalksand), which was divided into four divisions, ranging from 0.01 to 0.25 millimeter. The results of these experiments are plotted in figure 1, the weight in grams necessary to force the blade the required distance into the soil being plotted as ordinate and the moisture content in percentage of dry weight as abscissa. The same abscissas hold for both the "Kalksand" and quartz curves. The numbers on the curves represent the limiting sizes of the particles. In order further to distinguish the curves representing the composite samples, they have been drawn in dotted lines. From these curves it is readily seen that the penetration values are greater for the finer particles and that the values for the composite samples lie between the extremes.

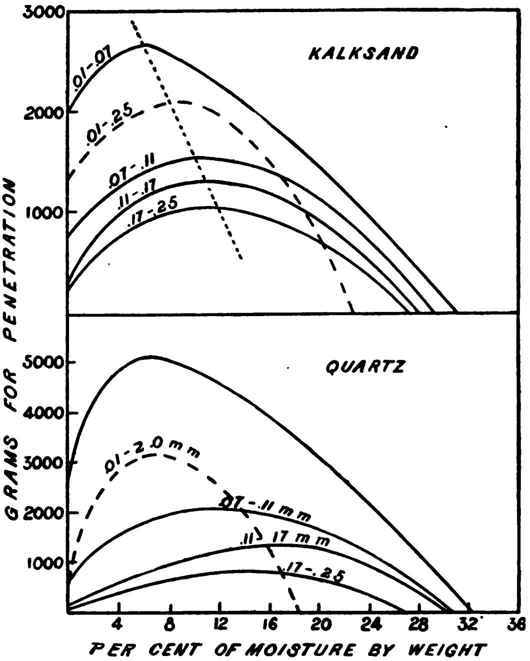

FIG. 1.—Influence of size of soil particles on penetration-moisture results for calcareous sand and for quartz, according to Puchner.

All these curves exhibit a maximum penetration value, from which it is evident that as the water content changes there is a corresponding change in at least this physical property, and that this particular water content has a special significance. As the size of particles varies the position of the maximum changes. In the case of "Kalksand" this has been indicated by drawing a straight dotted line through the maxima. In the case of the quartz curves the maxima do not seem to bear so simple a relation to each other; this may be due to the fact that the composite sample contains many large particles (2 millimeters). Although there were seven divisions for quartz, only four of the corresponding curves are shown in the figure, since the curves for the larger sizes lie too close to the axis abscissas to be conveniently plotted.

The relation of penetration to changing moisture content was studied by Puchner with certain principal soil constituents (quartz, humus, and clay), and cohesion values were obtained for the pure substances and for their mixtures. In this work the measurements were limited to one range of particles between 0.01 and 0.14 millimeter. These results have been plotted in figure 2. The curves for kaolin and quartz, humus and kaolin, and quartz and humus are drawn in separate divisions and each has its own set of ordinates.

In the case of kaolin and the mixtures in which kaolin predominates the force necessary for penetration increases steadily as the soil dries out. In the other samples the penetration curves show again a maximum point. The curves are also interesting, since the absolute values for penetration of the pure substance and of mixtures may be compared directly.

In discussing the value of cohesion measurements made on dry samples alone as indicating the physical condition of agricultural land, it was pointed out that the results so obtained were likely to be misleading, since under field conditions we seldom have to consider a dry soil. The truth of this will become apparent on examining the curves. Taking, for example, the case of humus and kaolin in the dry condition, the cohesion values vary in the different samples from about 500 to 12,000 grams. Under favorable cultural conditions the mixture "1 humus+2 kaolin" would probably contain about 35 per cent water, while "2 humus+1 kaolin" might contain from 20 to 40 per cent; the pure humus would ordinarily contain from 70 to 90 per cent. At these moisture contents, which would represent fair field conditions, the cohesion values would not be very widely different.

In his experiments Puchner made observations on many other factors relating to penetration, such as the influence of "single grain" and "crumb" structure, addition of chemicals, plant covering, frost, etc., to some of which reference will be made later. He also made quite as complete a study of soil cohesion by measuring the crushing strength of cylinders of his soil material, from which he obtained the same results and reached the same general conclusions, as follows:

(1) The cohesion of the soil, i. e., the force with which the soil particles are bound together, depends on the physical constitution of the soil, on the moisture content, and on the presence of various salts.

(2) Of the different soil constituents, clay has the greatest binding strength, while that of quartz, humus, and lime is less. The cohesion of the soil will therefore depend on the relative proportions of the different materials.

(3) The influence of water on the cohesion of soils is of great importance. In clay and clay earth the cohesion is greater as the water content diminishes, while in humus, quartz, and lime the soil particles are most strongly held together at a medium percentage of water.

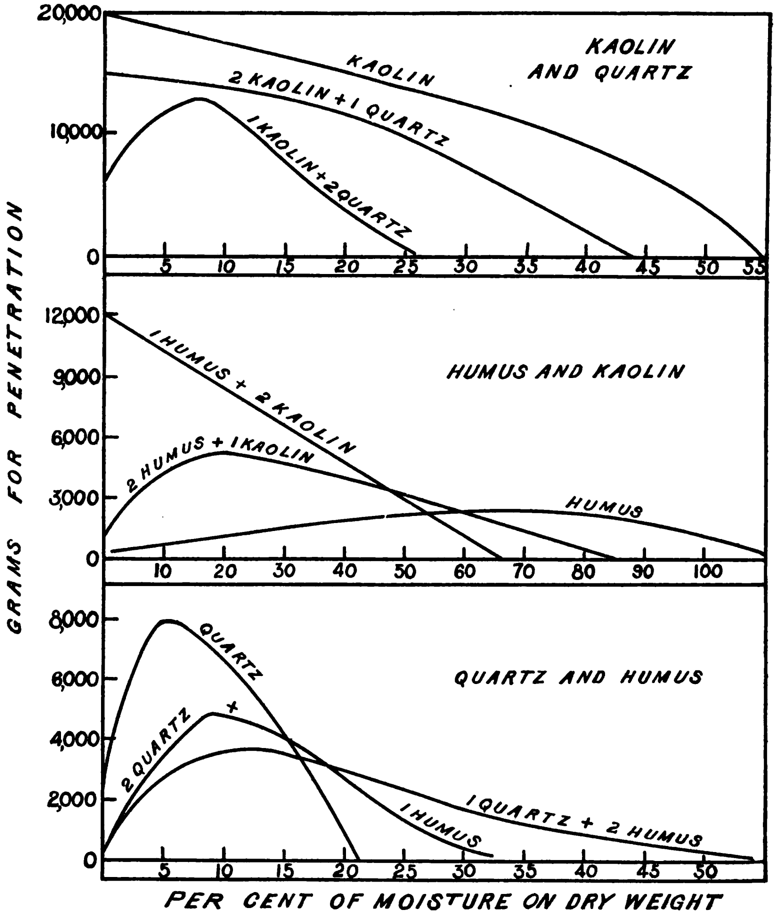

FIG. 2.—Penetration-moisture results for different soil components and mixtures of them, according to Puchner.

(4) The cohesion in any soil depends on the internal arrangement of the particles. It is greater in a "single grain" structure than in the "crumb" structure. If the soil particles are pressed together by an external force there results a proportional increase in the cohesion.

(5) Under otherwise similar conditions the binding strength of the soil is greater under crops than in fallow.

(6) The freezing of the soil greatly raises the absolute firmness.

(7) On the addition of lime the cohesion of clay is reduced under all moisture conditions, while the addition of potassium hydroxide and potassium carbonate increases the cohesion when the soil is dry, but reduces it at higher moisture content.

(8) In a consideration of the moisture condition most favorable for working a soil and best suited to placing it in most favorable mechanical condition, the question of cohesion should not enter, since with a medium water content (somewhere about 40 per cent of the total water capacity) the cohesion of most soils is at a maximum, and the soil can then be worked more easily into a crumbly condition. It is desirable to obtain the crumb structure, which is the best physical condition of the soil—i. e., the condition most favorable for crop production—even at the expense of greater labor.

It is quite evident from the work of other investigators that the cohesion or binding power is quite different for different soils and that it determines the penetrability. It is a matter of particular interest that the penetrability is closely connected also with the amount of moisture in soils. In order to investigate the influences of water on the physical condition and on the productiveness and apparent fertility of soils, a further study on penetration has been made.

RELATION OF PENETRATION TO MOISTURE CONTENT.

Object of experiments.

Unlike previous investigations in soil penetration, these measurements were not made primarily to study soil cohesion or to determine the resistance offered by various soils to cultural treatment. The purpose was rather to determine what constitutes a favorable physical condition for plant growth and how water affects this condition. It was assumed that the soil could be put into a most favorable condition as a cultural medium and that penetration measurements could be taken tentatively as an index of this state.

These considerations had an important bearing on the development of the methods used. It was pointed out by Puchner that a soil can best be put into a crumbly structure when it contains a medium amount of water. The importance of a crumb structure as a soil condition has long been known to agricultural men, and is earnestly sought in good agricultural practice. The ability of a soil to build a crumb structure or to form itself into aggregates is an important factor, determining the value of that soil as a medium for plant growth. The penetration work in previous investigations of soil cohesion has not been conducted under conditions best suited to plant growth. In fact the experimental procedure usually put the soil samples in a condition much worse than obtained in field practice. The soils were packed when dry, often with a pestle, so that the individual grains were worked into very close contact with each other, and the soils were then completely saturated with water, the samples being thus packed still closer. The desired water contents at which measurements were made were obtained by letting the saturated samples dry out. Such a procedure could hardly be said to duplicate field conditions. In order to study the influence of water upon the soil as a cultural medium it was desired to put every sample of soil into the most favorable state possible.

Experimental methods.

Neither absolute values for penetration, nor the comparison of these absolute values for different soil types were attempted; but rather the aim was to determine the variation in the penetration values for one particular soil at different moisture contents. Furthermore, a comparison of the penetration values for different soils can not be made, on account of frequent changes in the apparatus during the course of the investigation. No such variation as this, however, occurs during a set of measurements on any one soil sample, and these results are strictly comparable with one another.

In this problem one of the most serious difficulties encountered was so to control the handling of the soil sample and its packing that an agreement in results could be obtained between duplicate experiments. The difficulty in regulating the packing was rendered greater by the fact that the soils were to be examined in a loose condition, in which state even slight changes in the packing force produce large variations in the results. In studying the change of penetration with varying water content it was desired that all soil samples should have the same treatment. This it was impossible to do so long as the samples were worked by hand, and it was only possible when the process of packing was made purely mechanical. To this end a power-driven shaker (see fig. 27, p. 60) was devised, in which the soil samples were run through a coarse screen, after which they fell a definite distance through a funnel into the dish in which the penetration measurement was to be made. Since the screening was mechanical and the same in each case, the packing could be changed by varying the height through which the soil fell.

The apparatus for measuring the penetration (see fig. 30, p. 64) consisted of a long lever arm from the end of which was suspended a sharp conical tool of steel, free to swing in the vertical plane of the lever beam. This tool was forced a definite distance into the soil sample by weights added gradually to the middle of the beam. The unloaded beam and attachments were balanced by a counterweight hung beyond the fulcrum on the opposite end of the lever.

In making a penetration measurement the procedure followed was to make up a soil sample to about the desired moisture condition. The sample was run through the screening machine into the dish in which the penetration measurement was to be made. This dish was large enough so that several measurements were made on each sample, the mean of which was taken to represent the final value. The data for the complete variation of the moisture content were usually obtained by starting with air-dry soil. After the penetration value for this sample was obtained, enough water was added to the same lot of soil to increase the moisture content by a few per cent. This sample was in turn screened and measured, as before. The moisture content was thus gradually increased and measurements taken until the soil became too moist to work. The process could be reversed with equal success by letting the wet soil dry out to the desired point as long as the sample was screened at the same moisture content for which the penetration was determined. The amount of water present in the soil at each measurement was determined by drying a sample of the soil at 110° C. and calculating the moisture content to the dry weight, since this method gives moisture values which for any one soil are directly proportional to the actual amounts of water present. This method does not, however, give any idea of the moisture relations when comparison is made between different soils.

Results for Podunk fine sandy loam.

The first measurements of penetration were made for Podunk fine sandy loam, the mechanical analysis of which is given in Table IV.

TABLE IV.—*Mechanical analyses of Podunk fine sandy loam.*

Name of division.	Limits of size.	Percentage.	Name of division.	Limits of size.	Percentage.
	Millimeters.			*Millimeters.*	
Fine gravel	2.0 —1.0	0.0	Very fine sand	0.1 —.05	30.4
Coarse sand	1.0 — .5	.0	Silt	.05 —.005	18.8
Medium sand	.5 — .25	1.0	Clay	.005—.0	2.2
Fine sand	.25— .1	47.6			

This soil is seen to consist very largely of fine sand and very fine sand, along with considerable silt. It proved to be a soil particularly well adapted to an investigation of this kind, being very easy to work and not becoming sticky when water was added to it. In the air-dry condition it was found to hold about 0.3 per cent of water, and when completely saturated by letting water rise by capillarity into short columns it held about 30 per cent. The results of a series of penetration measurements on this soil are given in Table V.

TABLE V.—*Penetration-moisture relations for Podunk fine sandy loam.*

Moisture content.	Weight required for penetration.	Moisture content.	Weight required for penetration.
Per cent.	*Grams.*	*Per cent.*	*Grams.*
0.36	112	7.9	33
.92	73	10.5	38
3.9	28	13.4	42
5.8	28		

These results are shown graphically in figure 3, where the water content is measured on the axis of abscissas and the weight required for penetration on the axis of ordinates.

It can be seen from this that when the soil is put into the loosest possible condition the penetration measurements give a minimum between 4 and 6 per cent of water. This would indicate that as the moisture in the soil changes there is a definite variation in this physical property, and that one particular range of water content seems to have a special significance. It makes no difference in the result whether the water content be changed by adding water to the soil or by drying out a wet soil, for at one and the same moisture content the penetration value is a minimum.

As was pointed out in the introduction, there is a moisture condition in each soil which is recognized as the " optimum " water content, and is determined by the " feel " of the soil. To determine whether there is a relation between the critical amount of water as found in the above penetration work and this optimum water content, several samples of Podunk fine sandy loam, containing different amounts of moisture, were made up to optimum condition by practical greenhouse men. When the moisture determinations of the samples were made they were between 5 and 7 per cent of water, thus suggesting that the minimum in the penetration curve has a casual connection with the optimum water content, a quantity which up to this time has been purely arbitrary.

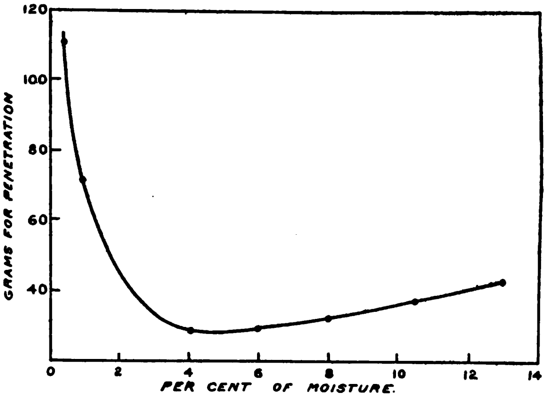

FIG. 3.—Penetration-moisture results for Podunk fine sandy loam.

Another set of penetration-moisture results, obtained in a similar manner except that the packing was somewhat greater, is given in Table VI.

TABLE VI.—*Penetration-moisture relations for Podunk fine sandy loam.*

Moisture content.	Weight required for penetration.
Per cent.	*Grams.*
0.3	178
2.6	53
6.0	48
11.6	54

These results are like the others in that they show a minimum at about 6 per cent of moisture content.

In working this soil preparatory to the measurements a great difference was noticed in its behavior as the amount of water was changed. The air-dry sample was of course in poor condition for agricultural purposes and was quite difficult to work because of the dusty nature and the compact state into which it settled. The addition of very little water produced a great change, as might have been predicted from the penetration curve; and although the soil was too dry for agricultural purposes, it was no longer dusty, seemed much lighter, and it screened and packed better. The soil sample giving the least penetration value responded most readily to working; it screened well, felt damp, light, and of an even texture. Beyond this point the soil began to feel wet and to show the effects of what might be called "free water"—i. e., water which does not seem to be an integral part of the soil. At 10 per cent water content the soil was still in fairly good condition, although it screened rather slowly, and beyond 14 per cent it could not be worked because of the difficulty of screening the wet soil. At this point it was evident that the soil was too wet for good plant growth. Although this method does not permit a study of soil condition in the neighborhood of the saturation point, it does allow sufficient variation to cover the range of soil moisture usually met under growing conditions, a range extending well above and below the optimum water content.

The penetration values according to this method form an interesting comparison with the plant growth on soils containing varying quantities of moisture. In the air-dry condition the soil is not able to sustain crops. When enough water has been added to the soil to enable it to support plant life, the penetration values drop very rapidly and are of the same order of magnitude as found at the minimum point. Beyond the minimum the penetration for Podunk fine sandy loam rises very slowly, which may be interpreted to mean that the physical condition of this soil changes but slightly over a range of several per cent, for the soil remains in very fair condition for plant growth over quite a wide range above 6 per cent of moisture.

It will be remembered that in his work on soil cohesion Puchner obtained maxima in his penetration-moisture curves, while the results just described showed minima. Puchner attributed his maximum values to an increase in the soil cohesion due to the presence of a definite amount of water in the soils. He also pointed out that this particular amount of water in the soil was most favorable for the formation of floccules or soil aggregates and the attainment of a crumb structure, due to this same increased cohesion. This appears to connect his observations with those here recorded and to show that the same forces which caused a maximum under the one method of procedure operated under a very different method to give a minimum. In order to test this point, a penetration-moisture study was made on Podunk fine sandy loam under conditions similar to those of the Puchner method. The results obtained are given in Table VII and graphically represented in figure 4. In order to make this result more easily comparable with other penetration results, we have included in the figure, using the same abscissas, a curve obtained for the same soil by the regular method of loose packing. Each curve, however, is given with its own ordinates. Although the penetration value for the critical point exhibited by the maximum is over one hundred times as large as the value given by the penetration at the minimum, and although the methods are widely different and represent very different conditions of internal arrangement of the soil particles, the agreement of the critical points in regard to the water content of the soils is very striking indeed. From this it is evident that in a soil some particular water content is of marked importance in determining the physical character of the soil, which property is undoubtedly determined by the distribution of the water.

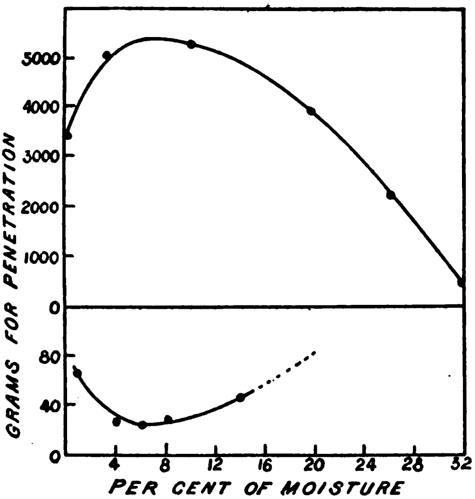

FIG. 4.—Penetration-moisture results for Podunk fine sandy loam by method of Puchner and by method of loose packing.

TABLE VII.—*Penetration-moisture relations for Podunk fine sandy loam, by the Puchner method.*

Quantity of water in soil.		Weight required for penetration.
Proportion of dry weight.	Proportion of total water capacity.	
Per cent.	*Per cent.*	*Grams.*
32.0	100.0	532
26.0	81.0	2,320
19.4	60.8	4,080
8.6	26.8	5,300
2.7	8.5	5,052
.0	.0	3,400

At the same time some experiments were made on the variation in the penetration-moisture relations when the soils were packed under different pressures. These results have a special interest in connection with the forms of the curves obtained by Puchner's method and by our method. In studying the effect of packing the soil, samples of Podunk fine sandy loam were prepared in the regular manner of loose packing, except that before the penetration measurement was made the desired pressure was applied to the surface of the soil by means of an apparatus designed for that purpose (see p. 62). The results of these measurements are given in Table VIII, and shown graphically in figure 5. The amount of the pressure per square centimeter used in packing the soil is given on each curve.

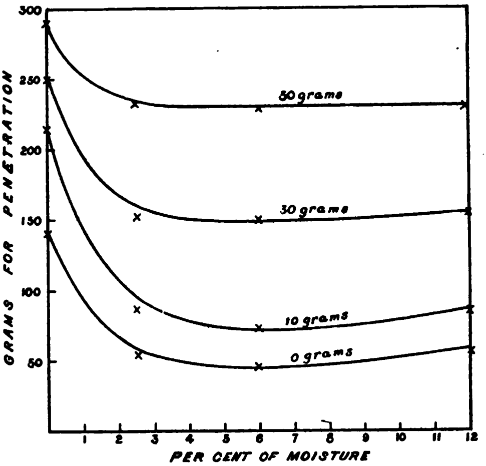

FIG. 5.—Penetration-moisture results with different packings.

TABLE VIII.—*Penetration-moisture relations for Podunk fine sandy loam, packed under different pressures.*

Packing force per square centimeter.	Moisture content.	Weight required for penetration.	Packing force per square centimeter.	Moisture content	Weight required for penetration.
	Per cent.	*Grams.*		*Per cent.*	*Grams.*
0 gram	0.0	178	30 grams	0.0	250
	2.6	53		2.6	155
	6.0	48		6.0	150
	12.2	54		12.2	154
10 grams	.0	237	50 grams	.0	291
	2.6	84		2.6	232
	6.0	72		6.0	230
	12.2	82		12.2	230

Although the pressures applied are not large and do not raise the penetration values anywhere near the point reached by samples measured according to Puchner's method, yet there is a well-defined tendency for the curves to flatten out as more pressure is applied. There is much less difference between the penetration values of the minimum and the dry state in the sample packed under 50 grams than there is in the sample packed under 10 grams pressure. The difference in the results obtained in the two penetration methods discussed is obviously one of packing. It would seem that upon increasing the pressure used in packing the loose samples a series of curves would be obtained ranging from those by our method, showing a minimum, to those by the Puchner method, showing a maximum. It was not deemed advisable at the present time to investigate this point further.

Results for Miami black clay loam.

Having found the above results for a sandy soil of low water capacity and poor in organic matter, the same method of study was applied to the Miami black clay loam, a soil of widely different character, a silty soil rich in organic matter, having a large capacity for water. The mechanical analysis of this soil is given in Table IX.

TABLE IX.—*Mechanical analysis of Miami black clay loam.*

Name of division.	Limits of size.	Percentage.	Name of division.	Limits of size.	Percentage.
	Millimeters.			*Millimeters.*	
Fine gravel	2.0 -1.0	1.2	Very fine sand	0.1 -0.05	6.2
Coarse sand	1.0 - .5	7.6	Silt	.05 - .005	53.4
Medium sand	.5 - .25	3.9	Clay	.005- .0	11.6
Fine sand	.25- .1	16.1			

The total water capacity of this soil is about 60 per cent, and in the air-dry condition it ordinarily contains about 8 per cent of moisture. When this soil was made up to optimum water content by field methods it was found to contain from 35 to 40 per cent of water.

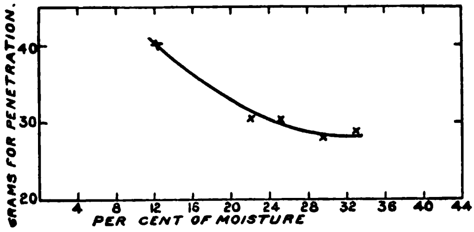

FIG. 6.—Penetration-moisture results for Miami black clay loam.

A penetration-moisture curve was made for Miami black clay loam when the soil was put each time into the loosest possible condition, the method being the same as already described for Podunk fine sandy loam. The results are shown graphically in figure 6.

When water was added to a comparatively dry sample the penetration value dropped to a minimum at 32 per cent moisture content. Enough water was added to the 32 per cent sample to increase the water content by several per cent, whereupon the soil proved too sticky to screen well. At 32 per cent the soil was in excellent condition, but on account of its clayey nature a few per cent of water caused a great change in the "workability." From this curve it is evident that as water is added to the dry soil, the cohesion is increased and the soil can be worked into aggregates. When the cohesion of the soil is greatest, as evidenced by a minimum in the penetration curve, the soil is in excellent physical condition.

Results for Leonardtown loam.

The next soil studied was quite different from those previously described, being a light-colored soil containing considerable clay and little organic matter, becoming rather sticky when wet, and on drying setting in a hard condition. The optimum water content for this soil was found to lie at about 15 per cent, a value midway between the optimum water content of the Podunk fine sandy loam and that of the Miami black clay loam. In the air-dry condition the soil contains about 1.3 per cent of water and when saturated holds some 34 per cent Several concordant sets of penetration results were obtained for this soil. Despite its tendency to become sticky when wet, it was possible to carry the penetration curve some distance beyond the optimum water content. Table X and figure 7 show the results of one set of measurements. The curve drops to a well-defined minimum at about 15 per cent of moisture, which is also the optimum water content.

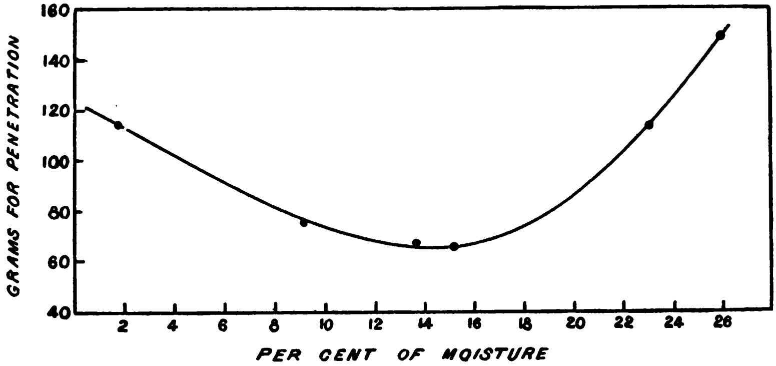

FIG. 7.—Penetration-moisture results for Leonardtown loam.

TABLE X.—*Penetration-moisture relations for Leonardtown loam.*

Moisture, calculated on dry weight of soil.	Weight required for penetration.	Moisture, calculated on dry weight of soil.	Weight required for penetration.
Per cent.	*Grams.*	*Per cent.*	*Grams.*
1.7	115	15.2	66
9.1	75	23.1	115
13.7	68	25.9	150

It was pointed out in the case of Podunk fine sandy loam that the form of the penetration curve might serve as an index to the character of the soil, and that for several per cent beyond the optimum water content the penetration curve rose very slowly, indicating that the physical properties change slowly and that the soil remains in fairly good agricultural condition. The penetration curve for

Leonardtown loam rises sharply, indicating a more marked change in the physical condition of the soil. Here also the curve corresponds to the field observations, for the favorable soil condition existing at 15 per cent of water rapidly disappears with a slight increase of water content. Further data on penetration for this soil are given in Tables XXIII and XXIV.

Results for Muck.

The next soil was studied as a check upon the conclusions reached in the previous work because it is an extreme soil type, being composed largely of organic matter and having a high water content. The mechanical analysis of this soil is not presented, as it would give little indication of the soil texture owing to the large quantity of organic matter present. In the air dry condition this soil ordinarily holds about 45 per cent of water, and when saturated some 220 per cent. The soil is in good condition for agricultural purposes over quite a wide range of moisture content, and it would be difficult to assign a close limit for the optimum water content as determined by the ordinary field method; however, it may be considered as between 120 and 140 per cent. The penetration measurements were made in the usual manner, the results being given in figure 8. From this it is seen that the penetration value reaches a minimum at about 120 per cent of moisture, which agrees well with the optimum water content.

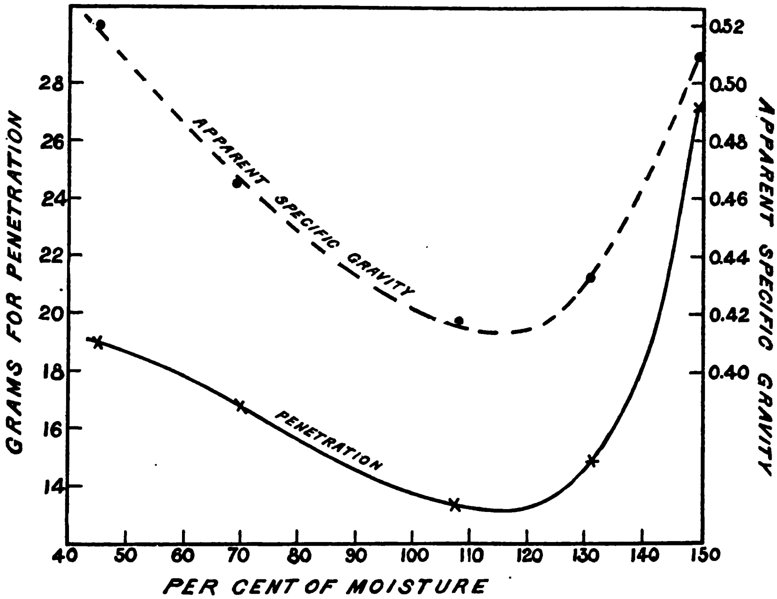

FIG. 8.—Penetration-moisture and apparent-specific-gravity-moisture results for Muck.

APPARENT SPECIFIC GRAVITY OR VOLUME.

PREVIOUS WORK.

In 1838 Schübler[a] studied the volume changes of soil by drying out wet samples until the weight no longer decreased. Representing the original volume as 1,000, he gives the volume to which the soils contracted on drying. In this way a comparison was obtained between different soil types. The results are shown in Table XI.

TABLE XI.—*Volume changes of soils on drying, according to Schübler.*

Material.	Percentage of original volume.	Material.	Percentage of original volume.
Quartz sand	100.0	Clay	88.6
Calcareous sand	100.0	Ordinary field soil	88.0
Gypsum	100.0	Fertile garden soil	85.1
Slate marl	96.5	Magnesium carbonate	84.6
Calcium carbonate	95.0	Kaolin	81.7
Potters clay	94.0	Humus	80.0
Clay loam	91.1		

The diminution of volume on drying was determined for six soils by Wolff,[b] who measured the change by means of a graduated cylinder. The influence of the size of the particles on the volume changes in soil was first studied by Haberlandt.[c] He used twelve soil samples, each of which was divided mechanically into ten separations. From the change in volume of the different soils and the water capacity, humus content, and mechanical analysis, conclusions were reached regarding the influence of different soil constituents on the volume changes. The experimental method consisted in measuring the change in volume of soil cylinders made from the damp earth. Haberlandt came to the following conclusions:

(1) The volume change which different closely packed soils undergo in drying out from a wet condition varies from 0 to 30 per cent of the original volume.

(2) Such volume changes are measured best in closely packed soils; loose soils are not well suited to measurement.

(3) Of the soil constituents humus has the most influence on volume change.

(4) It is probable that the volume changes of soils bear a linear relation to the fineness of the particles; yet this is only the case when these fine particles all have the same power to swell.

The volume changes due both to drying out and wetting were studied by von Schwarz.[d] He used four soil samples the mechanical analyses of which are given in Table XII. The volume changes are given in Table XIII.

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[a] Grundsätze der Agrikultur-Chemie, Leipzig, II, 82 (1839).

[b] Anleitung zur chemischen Untersuchung landwirtschaftlich wichtiger Stoffe, Berlin, 1899.

[c] Fühling's landw. Ztg., 7, 481 (1877).

[d] Erster Bericht über Arbeiten der k. k. landwirtschaftlichen Vers.-Stat. in Wein (1870–1877), p. 51.

Table XII.—*Mechanical analyses of soils used in volume studies by von Schwarz.*

Soil type.	Sands.				Suspended material.
	Coarse.	Medium.	Fine.	Very fine.	
	Per cent.	*Per cent.*	*Per cent*	*Per cent.*	*Per cent.*
1. Sand	0.0	96.34	3.11	0.55	0.55
2. Loam	0.0	19.87	31.70	30.39	18.04
3. Clay	0.0	0.0	0.0	4.53	95.47
4. Moor	Contained 82.6 per cent organic matter.				

Table XIII.—*Volume changes of soils on drying, according to Von Schwarz.*

Soil.	Decrease on drying.	Increase on wetting.
	Per cent.	*Per cent.*
1. Sand	0.0	0.0
2. Loam	17.0	19.2
3. Clay	29.8	42.4
4. Moor	60.2	....

An extended study of the volume changes on wetting and drying soils was made by Wollny.[a] In the apparatus devised by him for this study the soil samples were contained in a wide cup with a perforated bottom. This was surrounded by an outside dish so that the samples could be wetted by capillary water. On the surface of the soil rested a metal plate to which an upright rod was fastened. The weight of the rod and plate was counterbalanced by a weight running over a pulley. The upper part of the rod was notched so that it constituted a part of a rack and pinion that, on moving, revolved a pointer on a circular scale. The soil to be measured was packed into the containing dish in the dry state, the surface leveled, and the plate which moved the measuring mechanism was adjusted to the surface. By allowing the wet soil to dry, another measurement could be made. A measurement of the relation of volume change to size of particles on drying a soil gave the results in Table XIV.

Table XIV.—*Volume changes on drying soil separates, according to Wollny.*

Soil (quartz sand).	Size of particles.	Decrease in volume due to drying.
	Millimeter.	*Per cent.*
I	0.01–0.07	0.99
II	.07– .01	.17
III	.11– .17	.15
IV	.17– .25	.11
V	.25– .50	.0

From this table it follows that the change of volume in quartz sand is greatest for the finest material. Similar results were obtained when the dry soil samples were wet, although in this case the volume changes were greater, as can be seen from Table XV.

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[a] Forsch. auf dem Geb. Agr.-Phys., 20, 1 (1897).

TABLE XV.—*Volume changes on wetting soil separates, according to Wollny.*

Soil (quartz sand).	Size of particles.	Increase in volume due to wetting.
	Millimeter.	*Per cent.*
I	0.01–0.07	8.01
II	.07– .11	5.09
III	.11– .17	1.25
IV	.17– .25	.78
V	.25– .50	.0

Measurements were made on drying and wetting the principal soil constituents—quartz, clay, and humus, and their mixtures. The quartz used in this work was the finest size, varying from 0.01 to 0.07 millimeter. Table XVI gives the values obtained both in drying and wetting the samples.

TABLE XVI.—*Volume changes of different soil constituents and their mixtures due to changing moisture content, according to Wollny.*

Soil mixture.	Decrease on drying.	Increase on wetting.
	Per cent.	*Per cent.*
Kaolin	39.92	36.92
Kaolin, 2 parts + quartz, 1 part	33.17	30.90
Kaolin, 1 part + quartz, 2 parts	20.63	19.28
Quartz	.99	8.01
Quartz, 2 parts + humus, 1 part	2.86	10.84
Quartz, 1 part + humus, 2 parts	4.58	14.07
Humus	5.39	15.92
Humus, 2 parts + kaolin, 1 part	23.63	25.22
Humus, 1 part + kaolin, 2 parts	35.19	32.79

From this it is to be concluded that the volume changes in a soil are greater the more clay there is present and less the greater the amount of quartz. The humus causes an increase in the volume change when mixed with quartz, but has an opposite influence in mixtures of clay.

A number of other factors that influence volume changes in soils were studied by Wollny, such as effects of hydrates and salts, the effect of the arrangement of the soil particles, and the effects of rainfall and freezing, to some of which further reference will be made in the following pages.

RELATION OF VOLUME TO MOISTURE CONTENT.

Object of experiments.

From the work on volume changes just reviewed it is evident that variations in volume of greater or less magnitude occur in all soils when wetted and dried, which changes are influenced by a number of factors. The relation between the magnitude of these changes had been well established for a number of soils and under a number of different conditions. In none of the work, however, is there any reference to the variation in volume with the variation in moisture content. What has been measured may be designated the "total" change, which represents the difference in volume between the saturated and the air-dry conditions. Whether all or the greater part of the variation occurs over the range of low percentage of water or near the saturation point, or whether it is equally distributed over the entire range of moisture variation, has not been determined. In studying the effect of different amounts of water as affecting the physical state of the soil and determining favorable conditions for plants, it is of particular interest to know whether special quantities of water have a determining influence on the physical properties.

Variations in water content have all been in one direction, from the wet to the dry state, since there is no satisfactory way of adding regular intermediate percentages of water to a soil and leaving it in place for measurement. A soil could of course be molded into any convenient shape, saturated with water and measurements on the volume of the sample made as the water content decreased, without in any way disturbing the soil sample. The parallel results obtained by Wollny in the measurement of the "total" volume change in wetting and drying out a sample, indicate that the determinations in drying out a sample will probably give a true idea of the nature of the changes occurring.

Experimental methods.

Several different methods were used to measure the change in volume, because it was desired to have check methods and because different soil samples did not lend themselves equally well to the same method. The contraction along one dimension was measured rather than the actual volume change. The assumption was made that the contraction was the same in all directions and from the linear change for unit length the percentage volume decrease was calculated from the formula $D=1-(1-x)^3$, where x represents the unit linear change.

In one method, which will be designated the "soil column method,"[a] a cylinder of soil was supported in an inclined position on a metal form made by sawing a brass tube in half, longitudinally. A cylindrical brass follower was brought in contact with the upper end of the soil column. As the wet soil column dried out and diminished in length the brass follower moved downward, and this movement was measured by means of a micrometer screw, reading to 0.001 centimeter.

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[a] For full description see p. 67 and fig. 32.

This same micrometer was used at a different time to measure the contraction of samples contained in vertical glass tubes (see p. 65 and fig. 31) where a follower was also used in connection with the soil surface. This method will be designated as the "glass-tube method."

A different micrometer screw, reading to 0.0001 centimeter, was used in another method, where the soil sample was held in a cylindrical dish (see p. 68 and fig. 33), through the perforated bottom of which the sample could be saturated with water. A brass disk was set on the surface of the soil and the micrometer point brought in contact with this. For convenience this method will be designated the "micrometer method." A cathetometer was used to follow the contraction in soil samples supported in containing vessels having perforated bottoms. The point of an upright shaft, supported by a disk resting on the surface of the soil, was focused on the cross lines of the cathetometer telescope and thus the variation in the height of the soil surface was followed. This method will be called the "cathetometer method."

As a further indication of volume changes the apparent specific gravity of the soil was measured by weighing a unit volume in the condition in which it was worked. These observations were made at the same time that the penetration work was being carried on. In determining these data for the various soil samples it was necessary to level off the dish carefully, weigh dish and soil, and divide the weight of the soil by the volume of the dish.

Results for Podunk fine sandy loam.

It has been shown above that at a certain percentage of water the penetration results indicate that it is possible to work the soil into a maximum "looseness," which amount of water corresponds to the optimum water content. This observation was further checked by measuring the apparent specific gravity of the soil—the results being given in Table XVII.

TABLE XVII.—*Apparent specific gravity-moisture relations for Podunk fine sandy loam.*

Moisture content.	Apparent specific gravity.	Moisture content.	Apparent specific gravity.
Per cent.		*Per cent.*	
0.36	1.31	7.9	0.665
.92	1.21	10.5	.722
3.9	.69	13.4	.777
5.8	.655		

These data are better illustrated by the curve in figure 9, from which it is seen that the variation of apparent specific gravity with moisture content corresponds closely with the penetration-moisture results. On account of the greater accuracy attainable by weighing, the data given by the apparent specific gravity variations are even more concordant than those given by penetration measurements, which are more difficult to make with accuracy on account of the influence of small irregularities in packing.

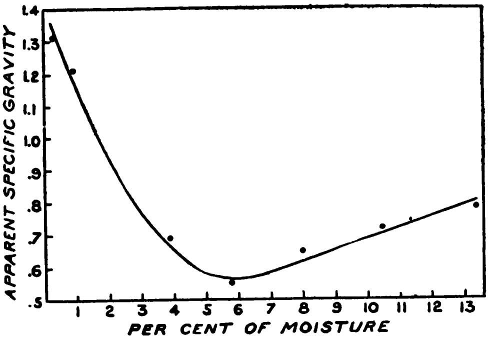

FIG. 9.—Apparent-specific-gravity-moisture results for Podunk fine sandy loam.

The apparent-specific-gravity data obtained in connection with the penetration measurements made when the soil was subjected to different packing pressures are shown by means of the curves in figure 10,

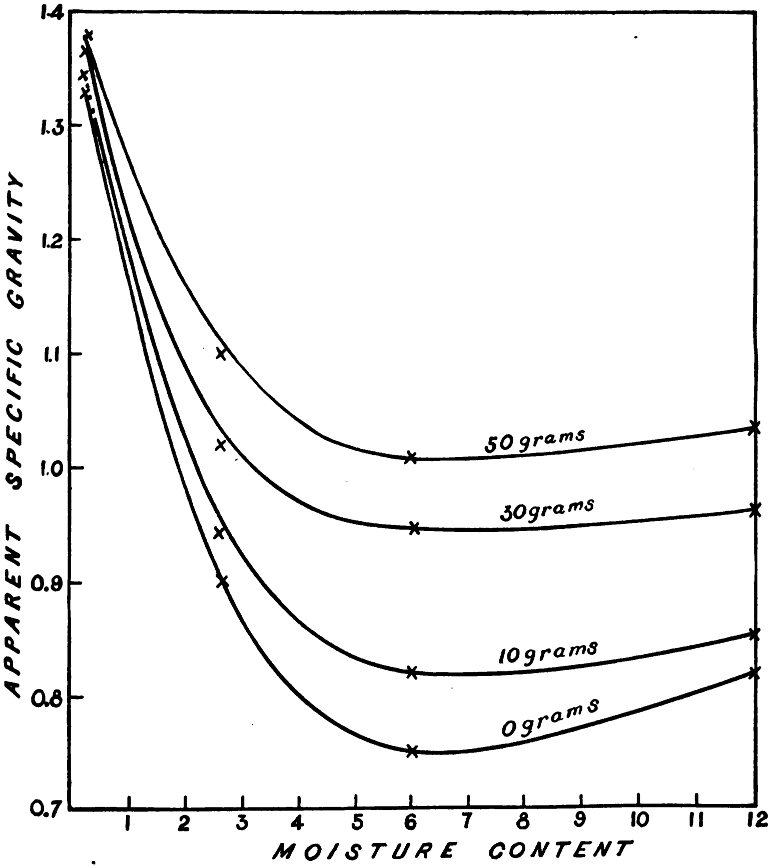

FIG. 10.—Apparent-specific-gravity-moisture results for Podunk fine sandy loam with different packings.

where the numbers on the curves represent the packing force per square centimeter. These curves are similar to the corresponding penetration curves, but they indicate more clearly the tendency to flatten out under increasing pressure due to the fact that the specific gravities of the dry samples are much closer together, so that the results of packing the loose soils at the optimum water content are more marked.

It can be readily seen from the work of Wollny on the "total" change of volume of soils that the measurement of the change of volume in sand with varying moisture content would present exceptional difficulties on account of the very small change of volume. When it is borne in mind that the volume is a cubical function of one length, the difficulty of obtaining accurate measurements on the linear contraction can be appreciated. In comparison with the readiness with which contraction measurements were made on some soils, the study of the volume change in Podunk fine sandy loam presented serious experimental difficulties. But these results were essential in order to compare the variations in this physical property with the changes in penetration and apparent specific gravity already given, and to complete a correlation of the individual properties that are dependent on the moisture content of the soil.

The results of a series of measurements on the volume changes in Podunk fine sandy loam as made by the micrometer method are given in Table XVIII.

TABLE XVIII.—*Volume-moisture relation for Podunk fine sandy loam.*

Moisture content.	Linear decrease.	Volume decrease.	Moisture content.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
32.9	0.0	0.0	11.5	0.022	7.13
29.8	.006	1.98	9.7	.022	7.13
29.0	.007	2.19	8.2	.022	7.13
27.7	.011	3.6	6.8	.022	7.13
22.7	.021	6.87	6.4	.0225	7.13
18.3	.022	7.13	5.4	.0255	8.36
16.0	.022	7.13	3.7	.0255	8.36
12.2	.022	7.13	2.0	.026	8.40

From the table it will be seen that the saturation point at which the measurements were started was about 33 per cent moisture content. As the sample dried out there was a gradual decrease in volume until about 18 per cent of water was reached when the contraction had amounted to 7.13 per cent of the original volume. From this point on there was very little, if any, contraction in volume over many per cent decrease in moisture content. When the soil reached about 6 per cent moisture content, however, a more rapid volume decrease commenced. At 2 per cent of water the volume decrease had reached

8.4 per cent of the original volume. These data are shown in another form in figure 11, where the moisture content is platted as abscissa and the per cent volume decrease as ordinate.

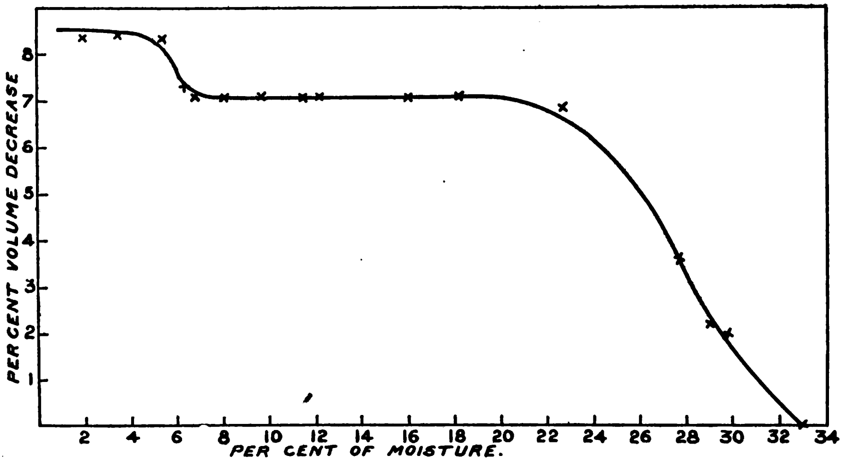

FIG. 11.—Volume-moisture results for Podunk fine sandy loam by the micrometer method.

In Table XIX and figure 12 is given a series of measurements made by the "glass-tube method," and these show the same variations as do the previous measurements.

TABLE XIX.—*Volume-moisture relations for Podunk fine sandy loam.*

[Length of soil column, 10 centimeters.]

Moisture.	Linear decrease.	Volume decrease.	Moisture.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
23.8	0.0	0.0	5.9	0.023	0.69
17.7	.015	.48	3.0	.043	1.30
9.3	.016	.50	1.6	.043	1.30
7.4	.016	.50			

The total percentage decreases are not the same by the two methods. As was pointed out in the chapter on penetration, the "absolute" values of these changes have no significance, but only the relation between the water content and the property being studied. It is to be noticed, however, that the measurements by the latter method were not begun at 33 per cent, but at 24 per cent, and if a similar range be taken on the curve of figure 11 the total volume changes by the two methods more nearly approach each other. Considering the curves

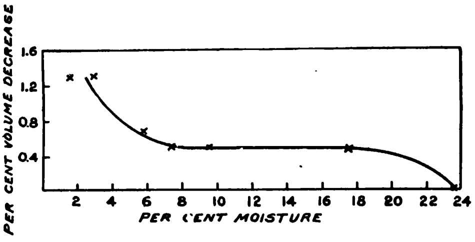

FIG. 12.—Volume-moisture results for Podunk fine sandy loam by the cathetometer method.

within the range of the moisture content covered in the penetration work—namely, 14 per cent to 0 per cent—it will be seen that from 14 to 6 or 7 per cent there is no appreciable change in volume in Podunk fine sandy loam, the loss of water over this range having no influence on the volume of the soil. In the neighborhood of 6 per cent, however, a change is noticeable, a loss of water beyond this point being accompanied by a diminution in the volume of the sample.

Thus, it follows that not only in the penetration but also in the aparent specific gravity a change occurs in the physical properties of the soil at about 6 per cent moisture content, which content is also the optimum. It is evident, therefore, that the optimum water content has an important physical significance and the work on volume contributes much to an understanding of the factors that operate at the optimum water content.

Results for Miami black clay loam.

Very satisfactory volume results were obtained in the measurements on the Miami black clay loam. The nature of the soil made it well suited to the soil column method of measuring volume change; because of its clayey nature and organic matter content it was able to retain the form of the soil column both in a very wet and a very dry condition. Further, the presence of the clay and organic matter caused greater volume changes, which added much to the ease of obtaining results.

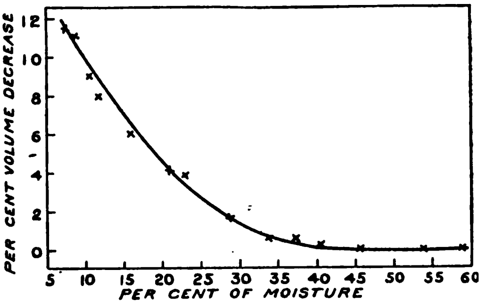

FIG. 13.—Volume-moisture results for Miami black clay loam by the soil column method.

A set of data obtained for Miami black clay loam on the volume changes with varying moisture content is given in Table XX and represented graphically in figure 13.

TABLE XX.—*Volume-moisture relations for Miami black clay loam by the soil column method.*

[Length of soil column, 14 centimeters.]

Moisture.	Linear decrease.	Volume decrease.	Moisture.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
59.0	0.0	0.0	20.9	0.195	4.1
54.0	.002	.0	16.2	.292	6.1
45.7	.002	.0	11.8	.383	8.0
40.4	.011	.2	10.8	.444	9.1
37.4	.022	.5	9.0	.537	11.1
34.0	.028	.6	7.6	.559	11.5
28.8	.078	1.6	6.7	.564	11.6
22.3	.181	3.9			

From this table it is seen that for moisture changes over a wide range near the saturation point there is no change in volume. At about 40 per cent, however, there begins a contraction in volume which continues down to the lowest limit to which the drying was carried. Another curve was obtained by the cathetometer method, the moisture content varying from the saturation point to well below the optimum. At the saturation end of the curve no variation in volume occurred, but at about 35 per cent moisture content a decided contraction began, which continued through the lower moisture contents. These data are given in Table XXI and figure 14.

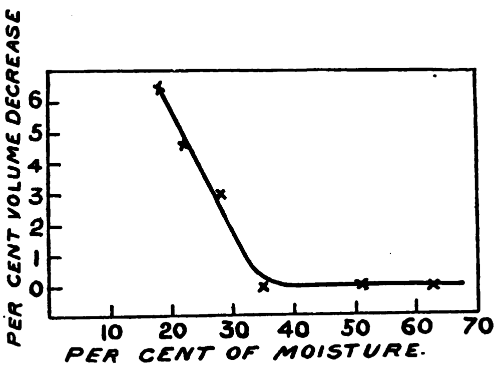

FIG. 14.—Volume-moisture results for Miami black clay loam by the cathetometer method.

TABLE XXI.—*Volume-moisture relations for Miami black clay loam by the cathetometer method.*

Moisture.	Linear decrease.	Volume change.	Moisture.	Linear decrease.	Volume change.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
61.2	0.0	0.0	28.2	0.04	3.1
51.8	.0	.0	22.6	.06	4.6
35.0	.0	.0	18.3	.08	6.5

Another set of results on the apparent specific gravity of the different samples is plotted in figure 15, from which it is seen that the results run parallel to the penetration data, as shown in figure 6. Thus, again the volume changes indicate that a change in the physical properties of the soil occurs in the region of the optimum water content.

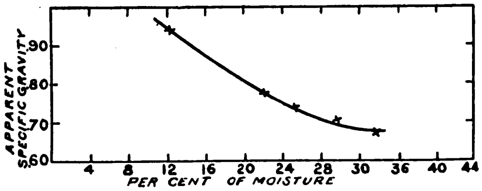

FIG. 15.—Apparent-specific-gravity-moisture results for Miami black clay loam.

Results for Leonardtown loam.

The data and curve for a set of measurements on the volume changes in Leonardtown loam are given in Table XXII and figure 16. This curve does not show a marked change in direction at 15 per cent moisture content, and has been added for the sake of completeness to illustrate what may be expected in volume measurements on a soil of this nature. Numerous attempts to take measurements of the volume changes were made with this soil, from which widely varying results were obtained. A few of the forms of curves resulting from different methods are plotted in figure 17, and show that the behavior of this soil is quite irregular.

TABLE XXII.—*Volume-moisture relations for Leonardtown loam by the micrometer method.*

Moisture.	Linear decrease.	Volume decrease.	Moisture.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
33.0	0.0	0.0	22.6	0.194	6.35
32.4	.029	.96	20.6	.209	6.81
30.0	.097	3.19	17.3	.227	7.32
29,2	.119	3.86	15.9	.230	7.46
27.2	.147	4.79	14.7	.235	7.63
26.2	.166	5.38	12.6	.239	7.76
24.2	.176	5.77	11.7	.241	7.90
23.6	.185	6.03			

The variable conduct of this soil may be attributed to its uncertain plasticity, due to the irregular distribution of clay in the soil. As the soil dries out the particles stick together, and when dry the whole becomes cemented into a very hard and compact mass. This cementing of the particles interferes with whatever tendency the changing moisture condition might have to alter the internal arrangement of the soil.[a]

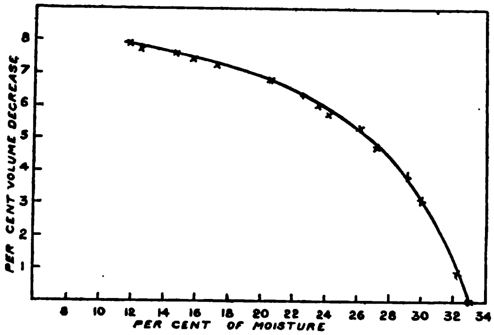

FIG. 16.—Volume-moisture results for Leonardtown loam by the micrometer method.

Upon examination of the curves in figure 2, in which are plotted the penetration results of Puchner, it will be seen that the measurements on clay samples show peculiarities very similar to those encountered in the present work. In the cases in which quartz and humus were in excess the penetration-moisture data all showed maxima in the curves. When kaolin was present in large amounts the penetration values increased steadily as the drying progressed, which action Puchner ascribed to the plastic nature of the material and to the hard, cemented character which the soil assumed on drying out. It is evident from the penetration results for Leonardtown loam that when the sample is worked up into condition at the different moisture contents, the cementing action accompanying drying out is largely prevented.

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[a] The subject of plasticity in clays has been discussed by many writers, and references to a few of the more important treatises are here given: Schlösing, Compt. rend., **74**, 1408 (1872); **78**, 1276 (1874); Jour. de l'agriculture, **9** iv, 50, 93, 140, 171 (1874) Hilgard, Forsch. auf dem Geb. Agr.-Phys., **2**, 441 (1879); van Bemmelen, Landw. Vers.-Stat., **35**, 69 (1888); Whitney, Bul. No. 4, Weather Bureau, U. S. Dept. Agr. (1892), p. 27; Ries Clays; Their Occurrence, Properties, and Uses. New York, 1906.

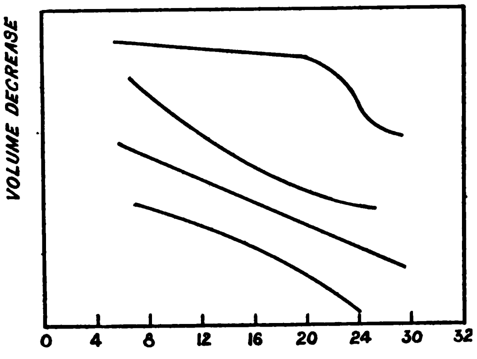

FIG. 17.—Volume-moisture results for Leonardtown loam by the soil column method.

The apparent specific gravity curve shown in figure 18 was plotted from the data contained in Table XXIII. A similar set of data is given in Table XXIV. In all cases there is a well-defined minimum at 15 per cent moisture content.

TABLE XXIII.—*Relations between penetration, apparent specific gravity, and moisture for Leonardtown loam.*

Moisture, calculated on dry weight of soil.	Weight required for penetration.	Apparent specific gravity.	Moisture, calculated on dry weight of soil.	Weight required for penetration.	Apparent specific gravity.
Per cent.	*Grams.*		*Per cent.*	*Grams.*	
2.8	77	1.07	15.0	43	0.828
6.0	59	.980	15.3	46	.822
10.4	48	.865	17.9	46	.828
12.4	49	.841	20.5	69	.868

TABLE XXIV.—*Relations between penetration, apparent specific gravity, and moisture for Leonardtown loam.*

Moisture, calculated on dry weight of soil.	Weight required for penetration.	Apparent specific gravity.
Per cent.	*Grams.*	
1.8	50	1.01
5.6	40	.812
11.0	34	.695
14.1	34	.690
17.3	40	.723

Results for muck.

This soil proved to be well suited for measurements on volume change by the soil column method, not only because it retained its form on contraction without developing large cracks, but also because it gave fairly large volume changes. The results of the series of values obtained for volume change with varying amounts of water by the soil column method are given in Table XXV, and shown graphically in figure 19.

Table XXV.—*Volume-moisture relations for muck by the soil column method.*

Moisture content.	Linear decrease.	Volume decrease.	Moisture content.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Centimeter.*	*Per cent.*
217.0	0.0	0.0	90.0	0.181	3.8
200.0	.004	.1	83.4	.214	4.46
154.0	.018	.33	67.0	.273	5.31
138.0	.052	1.03	51.1	.372	7.63

From the curve it will be seen that beginning at 217 per cent of moisture, which represents the saturation limit, there is very little decrease in volume over a wide range of moisture content. At 140 per cent of water there is a sharp contraction in the volume which continues down to 45 per cent, the air-dry condition.

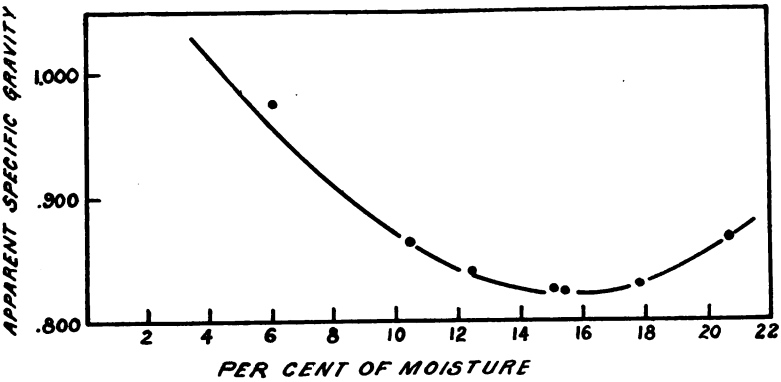

Fig. 18.—Apparent-specific-gravity-moisture results for Leonardtown loam.

A series of check results was obtained by the cathetometer method, and is given in Table XXVI and figure 20. The results are quite like those obtained by the column method, indicating that there is a large change between about 140 per cent of moisture and the air-dry condition. It follows that this soil exhibits the same critical changes in physical properties at the optimum water content as were found in the other soils.

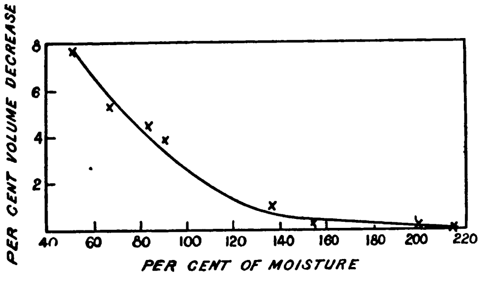

Fig. 19.—Volume-moisture results for Muck by the soil column method.

TABLE XXVI.—*Volume-moisture relations for muck by the cathetometer method.*

Moisture content.	Linear decrease.	Volume decrease.
Per cent.	*Centimeter.*	*Per cent.*
210	0.0	0.0
185	.0	.0
164	.0	.0
120	.01	.76
84	.03	2.4

In figure 8 corresponding results for penetration and apparent specific gravity are given, the abscissas being common to both curves. It will be seen that the two curves are similar, indicating that it is possible to work this soil into the loosest condition at 120 per cent of moisture, at which point the soil is in the best possible agricultural condition. On the addition of water beyond this point the soil soon becomes too wet to be easily worked, as might be predicted from the rapid rise of the penetration curve.

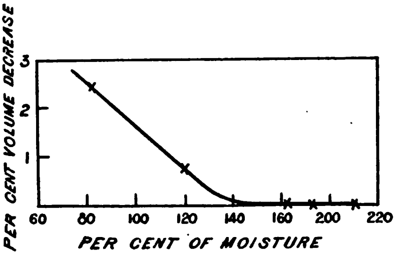

FIG. 20.—Volume-moisture results for Muck by the cathetometer method.

SUCCESSIVE WETTING AND DRYING.

Objects of experiments.

In studying the relation between volume change and moisture content one must consider what constitutes "natural" packing in the soil. It is known that there are large volume changes in soils under field conditions whenever the soil is dried or wetted. These volume changes render it highly improbable that the soil will stay in any condition of packing imposed by an external agency. It is a matter of common observation that when a soil is put into a loose condition by cultivation or other means and subsequently left undisturbed it will settle back in time nearly to its original volume. The relation between the change in volume due to settling and the change in volume due to a variation in moisture content was therefore investigated.

Experimental methods.

The methods of measuring the volume changes were the same as in the volume work described above. When the soil had gone through the process of drying out once it was wetted by capillary rise without in any other way disturbing it. A complete record of the volume measurements was obtained while the soil was drying out; the total change in volume due to wetting was observed without obtaining measurements for the intermediate moisture contents. This cycle could be repeated any number of times, and the variation in soil volume due to continued wetting and drying could be readily followed.

Results for Miami black clay loam.

The results of a set of measurements by the soil-column method for Miami black clay loam in which the original sample was in fairly loose condition are given in Table XXVII. For each cycle the volume decrease has been given in cubic centimeters and in per cent. In the last column is given the total volume decrease referred to the original volume. The separate curves are referred to the same standard for comparison, i. e., the original volume of the sample.

TABLE XXVII.—*Volume changes for the continued wetting and drying of a loose sample of Miami black loam.* (*Soil column method.*)

Cycle.	Moisture content.	Length of column.	Changes during separate dryings.		Total changes from original condition.	
			Linear decrease.	Volume decrease.	Linear decrease.	Volume decrease.
	Per cent.	*Centimeters.*	*Centimeter.*	*Cubic centimeters.*	*Centimeters.*	*Cubic centimeters.*
1	53.2	13.989	0.0	0.0	0.0	0.0
	41.1	13.989	.011	.2	.011	.2
	38.5	13.936	.064	1.3	.064	1.3
	25.2	13.904	.196	4.1	.196	4.1
	19.2	13.545	.455	9.3	.455	9.3
	9.5	13.366	.634	12.9	.634	12.9
	5.7	13.316	.684	14.0	.684	14.0
2	59.0	13.536	.0	.0	.464	9.8
	54.0	13.534	.002	.0	.466	9.8
	45.7	13.534	.002	.0	.466	9.8
	40.4	13.525	.011	.2	.475	10.0
	37.4	13.514	.022	.5	.486	10.3
	34.0	13.508	.028	.6	.492	10.4
	28.8	13.458	.078	1.6	.542	11.4
	22.3	13.455	.181	3.9	.645	13.7
	20.9	13.341	.195	4.1	.659	13.9
	16.2	13.244	.292	6.1	.756	15.9
	11.8	13.153	.383	8.0	.847	17.8
	10.8	13.092	.444	9.1	.908	18.9
	9.0	12.999	.537	11.1	1.001	20.9
	7.6	12.977	.559	11.5	1.023	21.3
	6.7	12.972	.564	11.6	1.028	21.4
3	58.3	13.469	0.0	0.0	0.531	10.5
	55.6	13.428	.041	.9	.572	11.4
	51.4	13.407	.062	1.3	.593	11.8
	37.2	13.373	.096	2.1	.627	12.6
	31.8	13.318	.151	3.2	.684	13.7
	22.1	13.195	.274	5.8	.805	16.3
	19.8	13.131	.338	7.2	.869	17.7
	15.5	13.000	.469	9.7	1.000	20.2
	12.3	12.858	.611	12.5	1.142	23.0
	9.4	12.809	.660	13.5	1.191	24.0
	7.8	12.793	.676	13.8	1.207	24.3
4	59.5	13.282	.0	.0	.718	14.6
	54.5	13.271	− .011	− .08	.729	14.5
	40.0	13.153	+ .029	+ .6	.747	15.2
	32.4	13.114	.068	1.4	.786	16.0
	21.0	13.107	.175	3.7	.893	18.3
	19.3	13.092	.190	4.0	.908	18.6
	14.9	13.027	.255	5.3	.973	19.9
5	56.0	13.218	.0	.0	.782	15.9
	34.8	13.151	.067	1.4	.859	17.3
	2.9	13.071	.147	3.1	.929	19.0

From the data for total volume change it can be seen that there is a decrease in volume on drying out the wet sample. When the dry soil is wet again, there is an expansion, which is not, however, as large as the previous contraction, so that the total effect for the cycle has been to reduce the volume of the sample. The effect of continually wetting and drying a loose sample of soil is better seen from the curves in figure 21, which have been plotted from the data given in the above table.

The volume decrease for the loose soil in drying from a saturated to an air-dry condition was about 14 per cent of the original. This change is represented by curve 1. On again wetting the dry soil, it still showed a volume of 10 per cent less than the original. If on drying out the second time the moisture content had been reduced as low as it was in the case of curve 1, the volume change would have been about 12 per cent. This can be seen by exterpolating curve 2 to a 5 per cent moisture content.

The volume change from the original condition is about 23 per cent; hence at the end of this drying the soil occupies 77 per cent of its original volume. Likewise when this dry sample was wetted again, the expansion was less than the previous contraction, so that at the end of the second cycle the sample was packed still more. The difference, however, between states 3 and 2 is much less than between 2 and 1. The volume occupied by the soil after the third wetting decreased 13.8 per cent on drying out, which indicates that, although the sample is packed more tightly, the contraction in passing from a saturated to an air-dry condition remains about the same. The results for the fourth and fifth dryings are represented by curves 4 and 5, and in general indicate that the changes due to successive wettings and dryings are more nearly identical and that the sample is approaching a condition of " natural " packing.

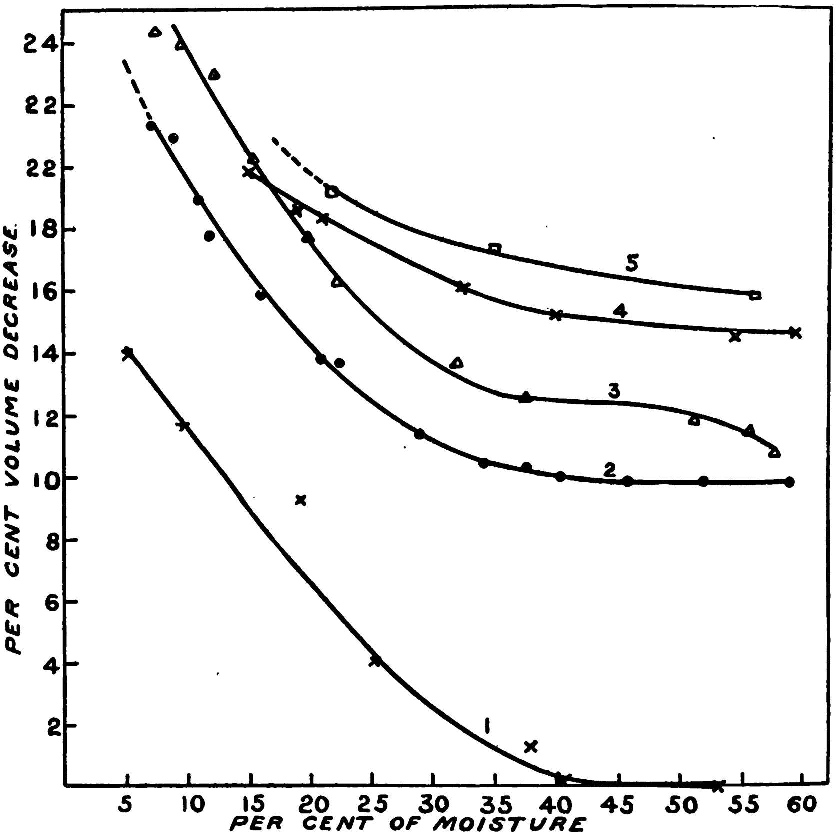

FIG. 21.—Volume changes with successive wetting and drying of loosely packed Miami black clay loam.

By the time curves 4 and 5 were obtained the soil column was in rather poor condition, owing to the fact that the cracks which formed on drying were not repaired in the subsequent wetting, so that the soil column developed points of weakness which interfered with the measurements of the total volume changes. For a continued series of this kind the soil column method would not prove so satisfactory as a method in which the sample is contained in a dish and the height of the soil surface measured. The former method has, however, the distinct advantage of being rapid, since the surface exposed per gram of soil is relatively very much greater than if the sample were contained in a cup. It is probable that the first three curves are more reliable than those obtained when the soil column was weakened by cracks.

These measurements on the continuous contraction of a loose sample of Miami black clay loam lead to the following conclusions:

(1) On drying and wetting a loose sample of soil there is a marked hysteresis effect in the volume changes, resulting in a total contraction in volume for a moisture-change cycle.

(2) On successive wettings and dryings this hysteresis becomes less and less. When it disappears altogether, the expansion on wetting will be equal to the contraction on drying and a condition will have been attained which may be designated a "natural" packing of the soil.

(3) Curves 1, 2, and 3 show that within limits the contraction in drying from a saturated to an air-dry condition is not greatly dependent on the packing.

Results for Muck.

A sample of Muck in a loose condition was found to give similar results for successive wettings and dryings. The contraction on drying out the sample the first time was 29.2 per cent of the original volume. On wetting it increased, however, only 7 per cent; as the result, therefore, of one cycle the volume was 22.2 per cent less than originally. On drying out the second time the volume decrease was 7.6 per cent, which made a total volume decrease of 29.8 per cent.

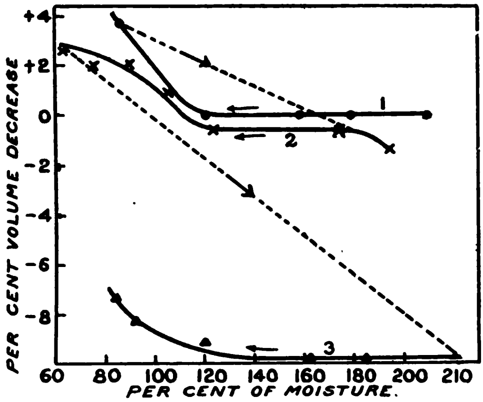

FIG. 22.—Volume changes with successive wetting and drying of closely packed Muck.

That the condition of natural packing in a soil does not represent the closest possible packing is evident from observations made on the successive wetting and drying of a very tightly packed sample of Muck. The soil, in a moderately moist condition, was closely packed into a cup and the change in volume with moisture content was followed by the cathetometer method. The results stated in Table XXVIII are expressed in the same manner as in Table XXVII, except that when the volume of the sample becomes greater than in the original condition the total per cent decrease in volume is assigned a negative value. The original saturated condition is taken as zero on the percentage volume change scale, and increases and decreases in volume are figured down and up respectively from this point. The results are more easily appreciated from the corresponding curves in figure 22. The curves have been numbered in the order of the successive dryings. On drying out the original sample the usual volume contraction is noted. The direction of the change (not the actual path) on wetting is indicated by the arrows on the dotted lines. In this case the expansion on wetting was greater than the previous contraction, and at the end of cycle 2 the sample is in looser condition and occupies a greater volume than at the end of cycle 1. Curve 2 again shows a contraction on drying and a much greater expansion on wetting. Curve 3 also shows the usual contraction on drying.

Table XXVIII.—*Volume changes for the continued wetting and drying of a closely packed sample of Muck (cathetometer method).*

Cycle.	Moisture content	Linear decrease.	Volume decrease.	Difference in volume.	Total volume decrease.
	Per cent.	*Centimeter.*	*Per cent.*	*Per cent.*	*Per cent.*
1....	205.0	0.0	0.0	0.0	0.0
	179.0	.0	.0	.0	.0
	158.0	.0	.0	.0	.0
	120.0	.0	.0	.0	.0
	86.0	.05	3.98	.0	3.98
2....	195.0	.0	.0	−1.32	−1.32
	175.0	.01	.76	.0	− .56
	123.0	.01	.76	.0	− .56
	105.0	.03	2.39	.0	+1.05
	92.5	.04	3.13	.0	+2.08
	75.0	.04	3.13	.0	+2.08
	64.0	.05	3.98	.0	+2.66
3....	210.0	.0	.0	−9.8	−9.80
	185.0	.0	.0	.0	−9.80
	164.0	.0	.0	.0	−9.80
	120.0	.01	.76	.0	−9.04
	92.0	.02	1.58	.0	−8.22
	84.0	.03	2.39	.0	−7.41

In comparing this with the curves representing the continuous changes in a loose sample (fig. 25) the effect of continued wetting and drying is seen to be in an opposite direction. It is possible therefore to pack a soil so tightly that on continuous moisture changes the volume will increase. This hysteresis effect will cease when the expansion due to complete wetting just equals the contraction due to drying out to the air-dry condition, and the soil will then be in the state of natural packing. It has been suggested that within narrow limits the change in volume on contraction was not greatly dependent on the packing. If this were not the case the influence of packing would have to be considered in measurements, such as were made by Wollny and others, on the " total " volume change due to wetting and drying. It has been made clear that unless the condition of natural packing is realized the volume decrease in drying will not be the same as the increase in the subsequent wetting. That the volume changes obtained by previous investigators (see Tables XIV and XV) on wetting a soil were different from those obtained for the same soil on drying was no doubt due to the fact that the samples were not in the condition of natural packing and that the hysteresis effects described above were encountered.

RATE OF EVAPORATION.

RELATION OF RATE OF EVAPORATION TO MOISTURE CONTENT.

Experimental methods.

Since vapor pressure, and hence rate of evaporation, varies with temperature, reliable results could be obtained only when the measurements were made at constant temperature. A large air thermostat was made for this purpose. In order to cut down radiation the walls were built double. The heating was done by electric lamps controlled by the Geer[a] form of electric thermo-regulator. The air was thoroughly stirred by means of a fan, driven from the outside by a motor. By means of this device the temperature could be maintained constant within 0.1° C. In order that the humidity might remain constant during evaporation the samples were put in desiccators over a relatively large surface of 95 per cent sulphuric acid, which maintained a partial vapor pressure of 0.1 millimeter mercury at 25° C., the temperature of the thermostat.

Thus by regulating the temperature and consequently the vapor pressure the conditions for evaporation were controlled satisfactorily.[b]

The method consisted of wetting to its saturation point an amount of soil equivalent to 20 grams of dry material. The weight of the bottle and soil was determined initially and at frequent intervals during the process of drying out in the desiccator. From the loss in weight and the time between successive weighings the rate of evaporation was calculated. From the observed weight of the soil and bottle and the dry weight equivalent of the soil, the moisture content at the time of weighing was calculated. The calculated rate of evaporation was based on the mean water content prevailing over the time in which the loss was occurring, i. e., the mean of the moisture contents calculated from two successive weights.

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[a] Jour. Phys. Chem., 6, 85 (1902).

[b] Under these conditions the rate of evaporation from a dish of water should of course be constant. This was tried experimentally with satisfactory results.

Results for Podunk fine sandy loam.

A series of measurements on the rate of evaporation for Podunk fine sandy loam is given in Table XXIX, and is represented graphically in figure 23.

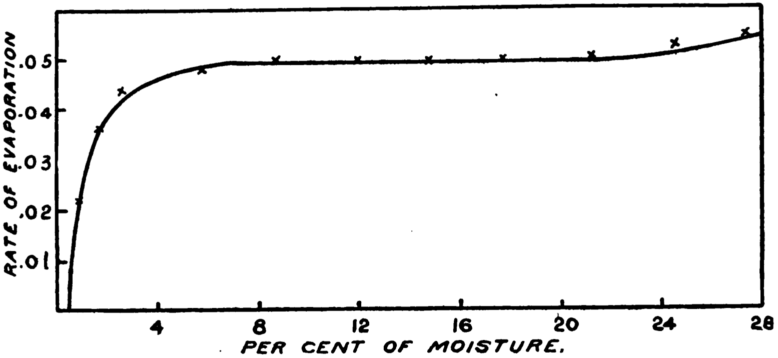

FIG. 23.—Rate-of-evaporation-moisture results for Podunk fine sandy loam.

TABLE XXIX.—*Rate of evaporation from Podunk fine sandy loam over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Gram.*	*Gram.*
27.4	19.5	1.0450	0.0536	8.7	14.5	0.7140	0.0492
24.2	4.5	.2362	.0525	5.8	9.9	.4712	.0476
21.3	18.7	.9210	.0493	2.4	4.0	.1732	.0433
17.8	9.3	.4595	.0494	1.7	2.0	.0719	.0359
14.8	15.3	.7495	.0490	.9	11.0	.2445	.0222
12.0	9.9	.4854	.0490	.3	2.0	.0097	.0049

The measurements on the rate of evaporation were begun when the soil held 28 per cent of water. The first evaporation was probably from the surface alone, so at first there is a small decrease in the rate as the water begins to evaporate from the pore spaces. Beginning at 22 per cent of water and extending over a wide range the rate of evaporation remains quite constant. At about 6 or 7 per cent a change takes place, for the rate decreases and continues to fall rapidly as the percentage of moisture decreases. Again, there is an obvious change in the physical properties of the soil at the optimum water content.

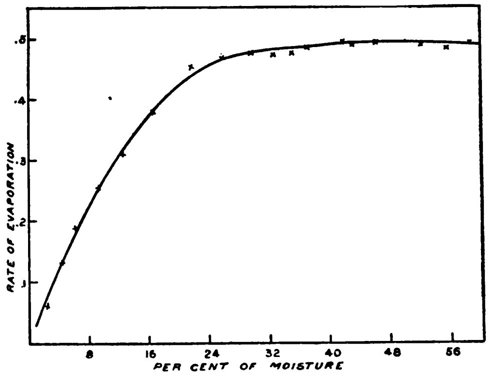

FIG. 24.—Rate-of-evaporation-moisture results for Miami black clay loam.

Results for Miami black clay loam.

On account of the high water content at the optimum in this soil the rate of evaporation method was exceptionally well suited to furnish a comparison of the soil condition at different water contents. The optimum for Podunk fine sandy loam lies so low that the change in the curve for the rate of evaporation might be supposed to be due to the relatively dry condition alone. In the present case the optimum lies about 30 per cent above the air-dry condition, so that changes in the character of the curve for rate of evaporation will be more significant. The data for this curve were obtained in the same way as for Podunk fine sandy loam. The data and the graphical representation are given in Table XXX and figure 24.

The evaporation curve which was started near 60 per cent is horizontal for about 20 per cent decrease in moisture content, showing a uniform rate above the optimum. At about 40 per cent, however, it gradually changes direction, the rate of evaporation falling.

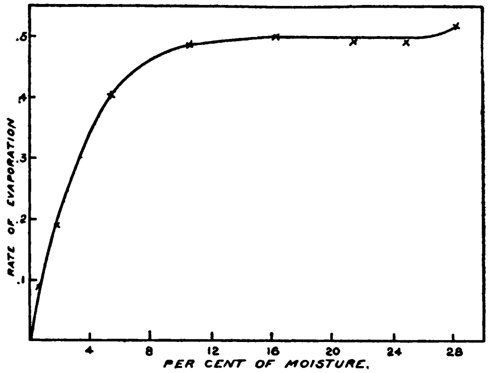

FIG. 25.—Rate-of-evaporation-moisture results for Leonardtown loam.

TABLE XXX.—*Rate of evaporation from Miami black clay loam over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Gram.*	*Gram.*
58.5	16.7	0.8198	0.0491	29.7	7.0	0.3321	0.0474
55.4	9.3	.4474	.0481	26.9	17.0	.7964	.0468
52.4	15.17	.7422	.0489	22.1	24.0	1.0879	.0453
49.4	9.9	.4802	.0485	17.1	24.0	.9109	.0379
46.4	14.5	.7155	.0493	12.9	26.25	.8108	.0309
43.4	9.9	.4808	.0486	9.5	22.25	.5716	.0257
41.0	11.0	.5427	.0492	6.7	24.5	.4694	.0192
37.5	11.0	.5411	.0483	5.1	22.75	.3056	.0134
35.4	6.5	.3099	.0477	3.7	23.75	.2136	.0090
32.6	17.5	.8295	.0474	2.7	24.25	.1470	.0061

For Miami black clay loam the studies in penetration, apparent specific gravity, and rate of evaporation all indicate that the critical moisture content which determines the physical properties of this soil lies between 35 and 40 per cent, which also is the optimum water content of the soil.

Results for Leonardtown loam.

The measurements of rate of evaporation from Leonardtown loam are given in Table XXXI and figure 25.

It has been shown that for this type of soil the volume relations at the optimum water content do not permit of very satisfactory conclusions. However, the penetration and evaporation measurements show critical changes at about 15 per cent of water, the optimum water content of the soil.

TABLE XXXI.—*Rate of evaporation from Leonardtown loam over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Gram.*	*Gram.*
28.2	19.0	0.9770	0.0517	10.7	24.5	1.1963	0.0488
24.9	7.25	.3555	.0490	5.5	22.75	.9193	.0404
21.6	19.25	.9538	.0495	2.0	24.25	.4560	.0188
16.4	22.0	1.0962	.0498	.7	24.16	.0904	.0037

Results for muck.

The results for this soil are given in Table XXXII, and have been plotted in figure 26. When the soil in a very wet condition was put over sulphuric acid in a desiccator there was at first a rapid drop in the rate of evaporation corresponding to the decrease as in the previous cases studied. The curves, however, indicate that for a wide change in moisture content it exhibits very little change in the rate of evaporation. At about 120 per cent there is a rapid decrease in the rate of evaporation, indicating that the critical moisture content has been reached. This decrease continues down to 30 per cent, at which point measurements were discontinued.

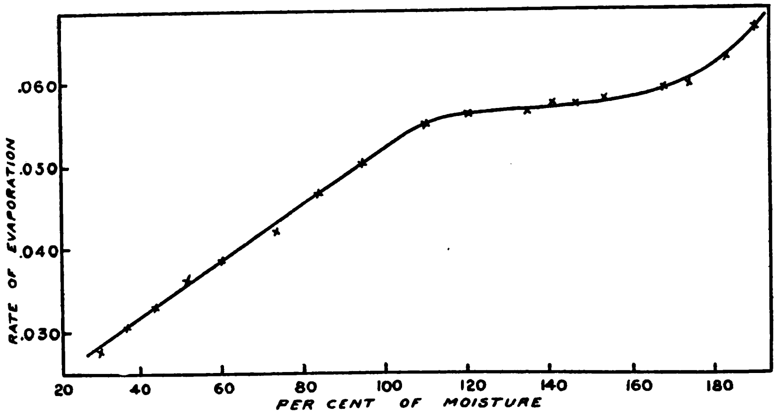

FIG. 26.—Rate-of-evaporation-moisture results for Muck.

TABLE XXXII.—*Rate of evaporation from muck over 95 per cent sulphuric acid at 25° C.*

Mean moisture content.	Time interval.	Loss.	Loss per hour.	Mean moisture content.	Time interval.	Loss.	Loss per hour.
Per cent.	*Hours.*	*Gram.*	*Gram.*	*Per cent.*	*Hours.*	*Grams.*	*Gram.*
190	9.5	0.6362	0.0669	110	24.0	1.3233	0.0551
183	15.2	.9590	.0632	95	24.0	1.2120	.0505
174	9.85	.5905	.0600	84	26.3	1.2332	.0469
168	14.5	.8639	.0596	74	22.1	.9329	.0423
154	10.0	.5813	.0581	60	24.3	.9388	.0387
147	13.0	.7474	.0575	52	23.0	.8352	.0363
141	6.5	.3744	.0576	44	24.0	.7958	.0331
135	17.5	.9893	.0566	37	24.0	.7372	.0307
121	17.0	.9591	.0564	30	24.5	.6851	.0279

MOISTURE DISTRIBUTION.

MOISTURE FILMS.

When to a dry soil a very small amount of water is added by putting the sample in an atmosphere saturated with vapor, there will be a direct condensation on the soil grains, and water will be held partly or entirely in thin films on the surface of the soil particles. Owing to an attraction between the particles and the water at the surface, this absorbed moisture is held with very great force, and the wetting of the soil grains is accompanied by an energy change of considerable magnitude. On wetting a mass of dry soil the formation of this film in the manner stated is accompanied by another effect due to the contact of soil grains. The films merge, so that a number of soil grains may be considered as being covered by one continuous film, and pulled together at the points of contact by the tension of the connecting film. Considering for the moment the formation of the films around the grains, it is evident that as more water is added to the soil and the films get thicker a point will be reached where the surface attraction of the soil particle is no longer strong enough to retain more water, since the surface force decreases rapidly as the distance from the surface increases.[a]

Before this point is reached, however, the thickness of the water films at the point of contact between the grains has been increasing owing to the film tension at the points of high curvature in the angles between the grains.[b] The thin, wedge-shaped angles between the grains will act then as capillary spaces and help to hold water. Since the surface films and capillary films merge, it is impossible to distinguish between them. The forces exerted by these films determine the changes in the internal arrangement of the soil particles and the physical characteristics of the soil.

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[a] Bakker, Zeit. phys. Chem., **56**, 95 (1906).
[b] Briggs, Bul. No. 10, Bureau of Soils, U. S. Dept. Agr. (1897).

EFFECT OF MOISTURE DISTRIBUTION ON VOLUME CHANGES.

When a soil is saturated with water the pore spaces are filled. Assuming that these soil capillary tubes are continuous and of uniform diameter, the capillary force holding the water is equal to the pull in an ordinary capillary tube of a similar size. In comparison with the capillary spaces occurring at the contact of the soil grains, these tubes are large, so that the capillary force exerted by them is relatively small. Since the water in the large spaces is not held by great force, it will be the first to evaporate and will have but little effect in changing the arrangement of the grains. As evaporation proceeds a point will be reached where the water begins to evaporate from the fine capillary spaces, which include the angles between the soil grains. At this point the forces of film tension become more noticeable. As the water held between the soil grains diminishes and retreats farther and farther into the angles, the surface film stretches, increasing the film tension and pulling the soil grains inclosed by it still closer together, thus producing a contraction in the volume occupied by the soil. The point where the effective film forces are just sufficient to cause changes in the internal soil arrangement will be designated the "critical moisture content." As evaporation continues still further the surface films around the grains and the capillary wedges held between the grains become thinner. The surface film forces continue to increase; hence the volume should steadily decrease until the soil reaches an air-dry condition.

It is evident from the data given for the volume changes in Podunk fine sandy loam that the above consideration is substantiated by experimental facts, and even more strongly by the volume changes observed with the other soils. Take, for example, Podunk fine sandy loam with about 14 per cent of water. At this point the large pore spaces contain considerable water, and as the soil dries out this water will be the first to disappear. Since the large capillary tubes constitute a relatively large part of the soil space available for water, they will hold a considerable percentage of the water when the soil is saturated. This will be particularly true in this soil, a sand, where the single intergranular spaces are large, owing to the size of the soil particles. The withdrawal of water from the larger pore spaces will therefore cause a large decrease in the moisture content of the soil. When the moisture content of the soil is about 6 per cent, the critical water content is reached and a change in volume begins.

It will be remembered that for volume changes in Podunk fine sandy loam a large volume contraction occurred between 33 and 18 per cent of water, between which limits the soil is too wet to ascribe the variation to the tension of the surface films. As the measurements were made on fairly loose samples of soil, it is quite possible that this volume change was caused simply by a gradual settling of the wet soil particles. When wet beyond a certain point a sand becomes incoherent. The soil aggregates seem to break down and the grains slip easily over one another, the excess of water acting as a lubricant and reducing the friction between the grains. It is possible that the volume changes occurring near the saturation point may also, in part, be due to a tendency of the free water to buoy up the soil grains and in this way decrease the packing of the grains by lowering the effective specific gravity of the individual grains. As the wet soil dries out, this tendency decreases and vanishes at a content of water a little below the saturation point.

The larger volume changes due to addition of water in clay soils is sometimes attributed to the presence of large amounts of colloidal material, which is supposed to imbibe the water and swell like starch grains. This view can easily be brought into agreement with the above theory of volume change. The question of absorption in a cell has been quite fully considered by Kauffler[a] and it has been shown by Patten[b] that absorption with imbibition can be considered as a special case under absorption. For our purpose, therefore, it makes no difference whether the volume change is due to action on the exterior surface of the particles or to imbibition accompanied by an increase in size of the particles. In the case of a peat soil, for example, it seems entirely reasonable that on account of the nature of the material a large change in volume is due to imbibition and swelling of the cells. There is no reason why a similar view should not be held for clay, although here it is quite possible to explain the phenomena without recourse to this idea. The volume changes in clay are very much greater than in sand. On account of the large difference in soil surface in a similar volume of the two classes, we would also expect the capillary and film effects in clay to be very much greater. The proportion of the relative areas exposed by equal volumes of very fine sand and of clay may be as great as 1 to 300, a difference which is quite sufficient to explain the large differences in volume changes in the two soils, on the basis of surface absorption and surface tension.

EFFECT OF MOISTURE DISTRIBUTION ON PENETRATION.

Having shown that volume changes in soils can be explained on the basis of the forces exerted by the capillary and surface films around the grains, and that the critical water content for volume-change and that for penetration are identical, it remains to be seen how the above considerations regarding the distribution of water in the soil explain the phenomena observed in the penetration experiments.

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[a] Zeit. phys. Chem., 43, 686 (1903).

[b] Trans. Am. Electrochem. Soc., 11 (1907).

Consider first the case of penetration under conditions of loose structure. The variations in the penetrability of the soil were attributed to the ability of the soil grains to arrange themselves into aggregates. In a dry soil the cohesion between the grains is that of one dry, solid body for another, and is readily seen to be small. The particles are thus quite free to move each other and tend to settle down into a compact condition. When a small amount of water is added to the soil, it gathers over the surface as films and settles into the angles between the soil grains. The cohesion of the soil particles increases and the action of surface tension promotes the formation of floccules and increases the possibility of building up the soil into a loose structure. As more water is added the thickness of the films and the amount of water held in the angles between the grains increase, the cohesion increases, and the soil responds better to cultivation. This effect reaches a maximum when the amount of water that can be held in this way reaches a maximum, and will be indicated by the fact that a minimum amount of force will be necessary to penetrate the soil sample. Since the loosely arranged soil grains in this condition occupy the smallest possible percentage of the total volume of the soil, the remainder of volume being taken up by air, the resistance to the introduction of a penetrating tool is a minimum at this point.

The further addition of water beyond the critical moisture content begins to fill up the larger pore spaces and to flood the soil. The soil aggregates begin to break down, thereby increasing the force necessary for penetration. This is shown by a gradual rise in the penetration curve beyond the minimum. Parallel results are, of course, indicated on the apparent specific gravity curves. The variations in penetration with moisture content is therefore related to differences in the distribution of water in the soil.

This same theory of soil moisture distribution accounts for the penetration results obtained by the Puchner method, where the critical water content for penetration was indicated by a maximum. As dry soil was packed into the containing vessel, the sample can be considered to represent a "single grain structure." The wetting of this dry sample must have been accompanied by an increase in volume, which caused an upward movement of the soil surface and a horizontal thrust upon the sides of the vessel. This acted as a packing force to the already close arrangement. The wetting of the soil also caused an increase in cohesion, as has been pointed out above. If the penetration measurements, therefore, had been made first on the dry sample and then on the sample corresponding to the maximum cohesion, there should be noted an increase in the penetration value. When a soil is saturated with water, the flotation effect tends to suspend the particles and decrease the packing. The excess of water, which renders the soil incoherent, acts as a lubricant, and increases the ease with which the soil grains slide over each other. At saturation this effect is greatest, so that the resistance to penetration is least. As the percentage of water decreases, this effect decreases, and the penetration values rise as shown by the curves. When the water disappears from the larger pore spaces, the critical moisture content and the point of maximum cohesion is reached, at which point the packing effect due to wetting the soil in a confined space is still in force so that the penetration value is high. As the amount of water further decreases there is a decrease in volume due to drying as already shown and a corresponding diminution of this horizontal thrust on the walls of the dish which causes a decrease in the penetration value. Therefore for a soil sample treated in this way the maximum force required for penetration is necessary at the critical moisture content. In the case of Podunk fine sandy loam the occurrence of the critical point in the penetration-moisture relations in both methods of measurement at about 6 per cent of moisture is not a mere coincidence, but is due to the same fundamental forces exerted by a certain quantity of soil moisture in its distribution upon the soil particles.

The change in the physical properties of a soil may be referred to one particular percentage of water only in case the distribution of the water in the soil is entirely uniform, which condition of course does not occur ordinarily. The distribution of water is affected in some measure by the size of the grains, irregularities in packing, gravity, and other variables which can not be controlled. The condition which has been described as influencing the internal arrangement of the soil grains can not then be correctly ascribed to a single point in the moisture variation, but must be considered as operating over a more or less narrow range of moisture content and subject to slight variation from sample to sample of one soil. Also, the measurement of this range may give slightly different results, depending on the method used. From a theoretical point of view the variation in range due to differences in the conditions prevailing does not detract from the value of the results or of the conclusions reached, since the cause of this variation is clear.

EFFECT OF MOISTURE DISTRIBUTION ON RATE OF EVAPORATION.

A further confirmation of the view that the content of soil moisture determines the physical properties of the soil is furnished by the investigation on the rate of evaporation of soil water from soils containing different percentages of water. It has been pointed out that a great difference must exist between the forces with which the water is held in the larger pore spaces and in the capillary angles between the grains. From this the conclusion follows that there must be a corresponding difference in the rate of evaporation.

As the water evaporates out of the larger pore spaces, the rate of evaporation will be determined by diffusion and by the forces of capillarity. Since a considerable quantity of the total soil water is held in the larger pore spaces and since the capillary pull in these spaces is not great in comparison with the forces exerted in the fine angles between the grains, the influence of capillarity upon evaporation from the large spaces will be relatively small. In relation to the rate of evaporation much of the intergranular space can be considered to be of the same order of magnitude, for which reason the rate of evaporation over a considerable range will not decrease very rapidly while the soil is drying out. As the evaporation continues the water held in these pores will disappear, and the soil water will be distributed almost entirely in the fine capillary angles between the soil grains and on the grains as films, where the greater capillarity holds it more strongly. Below this critical moisture content there will be a gradual falling off in the rate of evaporation, due to the increasing attractions between the water and the soil, causing a lowering of the vapor pressure of the absorbed films. Where the thickness of the film is such that the surface attraction just begins to cause a lowering in the vapor pressure of the film, the equilibrium point between the soil moisture and a saturated atmosphere of water vapor is reached, and in such an atmosphere no further evaporation of water from the soil grains takes place. In the open air, however, we are not dealing usually with a saturated atmosphere, and so evaporation will continue from the soil, but under constantly decreasing vapor pressure of the absorbed water, which in turn will cause a corresponding decrease in the rate of evaporation. When the vapor pressure of the soil films corresponds to the partial pressure of the moisture in the atmosphere, evaporation will cease, equilibrium having been reached between the vapor in the air and the film water.

Below the critical moisture content there will be a decrease in the rate of evaporation due, first, to slower diffusion of the water vapor from the finer capillary spaces, and, second, to an increase in the film tension accompanied by a decrease in the vapor pressure of the film water. These two effects merge gradually one into another, so that a smooth curve showing the decrease in evaporation is the result, the rapid decrease in evaporation beginning when the water in the larger pore spaces has nearly disappeared.

CRITICAL MOISTURE CONTENT AND MOISTURE EQUIVALENT.

That there is a connection between the critical moisture content and the distribution of soil moisture follows, also, from recent work done in this Bureau.[a] By means of a centrifugal machine a wet soil sample was subjected to a force about 3,000 times that of gravity, which tended to throw the water from the soil. Even when subjected to such a force it was impossible to reduce the soil sample to an approximately dry condition; in fact, the resulting soil samples contained enough moisture to correspond to good field condition. It is evident from this that part of the water is held in the soil by very strong forces. The only moisture removed from the soil was that held in the larger pore spaces. When the moisture content of the soil is reduced to the point where the water is held in the form of films and as capillary water between the soil grains, it is retained more tenaciously. It was also pointed out that the amount of water removed from the soil is not directly proportional to the centrifugal force used; that is, the soil can be reduced from very wet to a medium condition by a relatively small force. If at this point the speed be doubled, which means that the centrifugal force will be quadrupled, the further reduction of moisture content is comparatively small. This is in agreement with the conclusions reached from the present studies on the rate of evaporation from soils. Instead of measuring the retentiveness of the soil in terms of centrifugal force, here the effect of such a retentiveness on the rate of evaporation has been measured. When the soil moisture is held in the larger pore spaces, the rate of evaporation is fairly constant and not very much less than would be obtained under similar conditions from a free water surface. In other words, the retentiveness of the soil is not very great as indicated by the rate at which that part of the soil moisture evaporates. However, when the critical moisture content is reached, the rate of evaporation immediately begins to decrease, indicating that the soil water is held by greater forces in the finer capillary spaces. As the water surfaces retreat farther into the angles between the grains and the films on the grains become thinner, the forces holding the soil moisture in place increase; this in turn produces a decrease in the rate of evaporation. The results obtained by the centrifugal method agree with the rate of evaporation results, indicating the point at which the larger soil forces come into play. To compare these two methods of studying the distribution of soil moisture one may use the measurements of Briggs and McLane on Norfolk fine sandy loam and the measurements above recorded on Podunk fine sandy loam. The Norfolk fine sandy loam very closely resembles the Podunk fine sandy loam in its physical characteristics. This similarity is shown in part by the comparison of the mechanical analyses of the two soils given in Table XXXII.

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[a] Briggs and McLane, Bul. No. 45, Bureau of Soils, U. S. Dept. Agr. (1907).

TABLE XXXIII.—*Mechanical analyses of Podunk fine sandy loam and of Norfolk fine sandy loam.*

Soil.	Fine gravel, 1 to 2 millimeters.	Coarse sand, 1 to 0.5 millimeter.	Medium sand, 0.5 to 0.25 millimeter.	Fine sand, 0.25 to 0.1 millimeter.	Very fine sand, 0.1 to 0.05 millimeter.	Silt, 0.05 to 0.005 millimeter.	Clay, 0.005 to 0.0 millimeter.
Norfolk fine sandy loam.......	0	0.5	4.8	54.6	13.4	18.1	8.5
Podunk fine sandy loam.......	0	0	1.0	47.6	30.4	18.8	2.2

From this comparison it is seen that both soils contain a larger percentage of fine sand than of any other separate and that the quantities in the two soils are comparable. The Podunk soil contains somewhat more very fine sand than the Norfolk soil. The amount of silt is the same in both cases, but the amount of clay in the Podunk fine sandy loam is less than in the Norfolk fine sandy loam. By means of the centrifugal method the "moisture equivalent" was found to be 6.5 per cent of moisture. The critical condition of soil moisture for Podunk fine sandy loam, determined by the rate of evaporation method, was found to be 6 per cent, which is in agreement with the critical moisture value for this same soil as determined from the penetration and volume-change studies. The value obtained from the similar Norfolk fine sandy loam by the centrifugal method is just a little higher, which may easily be attributed to the higher clay content of that soil, since we know that the clay in a soil exerts a large influence on its water-holding power. As no determinations are available for the "moisture equivalent" of Muck or of the Miami black clay loam, there is no basis for comparison of these results. It is possible, however, to compare the sample of Leonardtown loam used in our investigations with a Hagerstown silt loam and a Clarksville silt loam, studied in the centrifugal work of Briggs and McLane.

A comparison of the mechanical composition of these three soils is given in Table XXXIV.

TABLE XXXIV.—*Mechanical analyses of Leonardtown loam, of Clarksville silt loam, and of Hagerstown silt loam.*

Soil.	Organic matter.	Gravel, 2 to 1 millimeters.	Coarse sand, 1 to 0.5 millimeter.	Medium sand, 0.5 to 0.25 millimeter.	Fine sand, 0.25 to 0.1 millimeter.	Very fine sand, 0.1 to 0.05 millimeter.	Silt, 0.05 to 0.005 millimeter.	Clay, 0.005 to 0.0 millimeter.
Leonardtown loam ...	....	0.1	1.2	0.9	3.1	6.4	70.9	16.7
Clarksville silt loam ..	1.2	1.2	1.4	.9	2.0	5.6	73.2	14.8
Hagerstown silt loam.	1.0	.3	.6	1.5	9.1	10.5	60.3	17.4

Clarksville silt loam more closely resembles the Leonardtown loam than does the Hagerstown silt loam. In all of these soils silt is in excess, varying from 60.3 to 73.2 per cent for the three soils. As regards this point, the Leonardtown and the Clarksville soils are closely comparable. The clay contents are about the same, being slightly higher in the Hagerstown silt loam. The "critical moisture centent" was found to be about 15 per cent for the Leonardtown loam. The "moisture equivalent," as determined by the centrifugal method, for the Clarksville soil was 15.1 and for the Hagerstown sample 16.5. From the close similarity in the mechanical composition and in the moisture values given, it would appear that the *critical moisture content* corresponds to the *moisture equivalent* as determined by the centrifugal method, as well as to the optimum water content, as determined by plant growth and cultural practices.

OPTIMUM WATER CONTENT AS REGARDS PLANT GROWTH.

The usual definition of optimum water content is that amount of water in the soil which is best suited to plant growth. But no emphasis has been placed on this during the course of the previous discussion, where it has been spoken of more often as the amount of water determining the best physical condition of the soil. It can be shown that the amount of water determining the best physical condition of the soil is generally the amount of water most favorable to plant growth. In this connection some evidence is given by Heinrich,[a] who determined the amount of water present in the soil when wilting of plants begins. In the six soils used determinations were made of the point of saturation, of the moisture content at which plants wilt, and also of the hygroscopic water content. This last was done by spreading the soil on a watch glass and exposing it for a week to an atmosphere saturated with water vapor. The results of this investigation are given in Table XXXV.

TABLE XXXV.—*Relation between hygroscopic moisture content and moisture content at which plants begin to wilt, according to Heinrich.*

Soil.	Water content at saturation.	Hygroscopic water content.	Moisture content at which plants begin to wilt.
	Per cent.	*Per cent.*	*Per cent.*
Coarse sand	26.5	0.42	1.5
Medium fertile garden soil	43.9	1.68	4.6
Infertile sandy muck	41.4	.97	6.2
Sandy loam	43.3	2.40	7.8
Very fertile calcareous soil	38.3	3.65	9.8
Peat soil	274.0	20.6	49.7

From this table it is evident that hygroscopic water is not sufficient to supply the needs of a plant, but it indicates also that the plant can exist on a relatively small amount of water. In comparison with the moisture content at which wilting occurs, the amount present in the soil at the critical moisture content is large indeed, and seems to be entirely sufficient for good plant growth. A possible objection is that the optimum water content is not the same for all plants, but from the above consideration it is evident that at the critical water content enough water is present for a good, if not an optimum, plant growth. In further experiments on two soils in continuation of the experiments just described the wilting points were determined for a large number of field crops. These results are given in Table XXXVI.

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[a] Zweiter Ber. Landw. Vers.-Stat. Rostock, 1894, 19.

TABLE XXXVI.—*Moisture content at which wilting begins for two soils, according to Heinrich.*

Plant.	Moisture content at which plants begin to wilt.	
	On calcareous soil.	On peaty soil.
	Per cent.	*Per cent.*
Oats	8.4	3.23
Barley	9.98	33.3
Rye	9.55	32.8
Wheat	....	43.6
Corn	7.91	....
French rye grass (*Arrhenatherum elatius*)	....	33.2
English rye grass	....	33.1
Meadow foxtail	....	34.2
Soft brome grass	....	32.8
Red clover	10.28	34.3
Sweet clover	8.77	....
Lambs clover	9.24	....
Crimson clover	....	34.1
Alfalfa	8.9	....
Vetch	....	35.3
Esparcet	9.92	....
Fire bean	11.04	....
Horse bean	11.30	....
Potatoes	5.07	41.4

Considering the possible variations due to the difficulty of making close representative moisture determinations in soils and the experimental difficulty of correctly judging the time of wilting, there is a striking agreement in the above results for various plants. The average for the calcareous soil is about 9 per cent of water, from which figure there is no striking variation in any of the cases considered, and the average for the peat is about 34 per cent of water.

The general belief that different plants require different optimum water contents in the soil seems to be a result of observations on the total amount of water that the plant actually requires rather than on the percentage in the soil best suited to its needs. The transpiration in one plant may be greater than in another, and the corresponding demand for water would be greater. Investigators in this field have usually supplied the extra amount of water demanded for this larger transpiration by increasing the total water content of the soil rather than by supplying more water as it is needed. That is, instead of gradually supplying a larger amount of water and maintaining the moisture content of the soil near a constant percentage, the same result is obtained by increasing the percentage of water in the soil at one time. The idea that there are different optimum water contents for the same soil for different plants may, therefore, be an outgrowth of the prevailing methods rather than of critical experimentation. Moreover, the idea that there are different optimum water contents corresponding to different plants has apparently been confused with the fact that some plants have more endurance under adverse moisture conditions than have others. These same plants may be able to grow in a large excess of water without great apparent injury, but actually require less for more favorable growth. The fact that one plant can tolerate larger amounts of water than another without serious injury does not alone justify the conclusion that the optimum water content differs for each.

From this work, showing the moisture content approximately constant with any one soil at which wilting of different plants begins and from the other considerations presented, it seems probable that the optimum water content is that which makes for the greatest aeration, loosest structure, and, in general, most favorable physical condition of the soil.

APPARATUS AND METHODS.

SCREENING APPARATUS.

In beginning work on penetration of soils in the loose condition, it was recognized that there existed a serious difficulty in obtaining a uniform packing and so arranging the conditions that the same grade of packing could be obtained on successive trials, thus insuring duplicate results. A preliminary investigation was made on the effect of packing on penetration. The firmness of the packing was determined from the weight of the soil, since the measurements were all made under one moisture condition and the soil was leveled in such a way that the same volume was always obtained. The change in packing was effected by jarring the dishes and by varying the method in which the soil was put into the containing vessel. The results of such a series of measurements on Leonardtown loam containing 9.1 per cent of water are given in Table XXXVII.

TABLE XXXVII.—*Influence of packing on penetration.*

Weight required for penetration.	Weight of soil.
Grams.	*Grams.*
70	1,785
75	1,808
85	1,830
113	1,902
175	1,965

When these results are plotted, using the weights of the soils as abscissas and the weights for penetration as ordinates, a smooth curve is obtained, showing that the penetration is not in direct proportion to the weight, but increases more rapidly. But for a small variation in packing, such as would be met under ordinary experimental conditions, the penetration is, for all practical purposes, a linear function of the packing. This is confirmed by the following measurements made on Leonardtown loam, which held about 15 per cent of water, its optimum water content.

TABLE XXXVIII.—*Influence of packing on penetration.*

Weight required for penetration.	Weight of soil.
Grams.	*Grams.*
64	1,702
71	1,719
87	1,739

These results when plotted lie on a straight line and indicate that soil variations or manipulations cause considerable differences in packing which, in turn, interfere with all measurements on penetration. The importance of having a satisfactory method of packing is therefore evident. Uniform packing is realized only when the process is entirely mechanical.

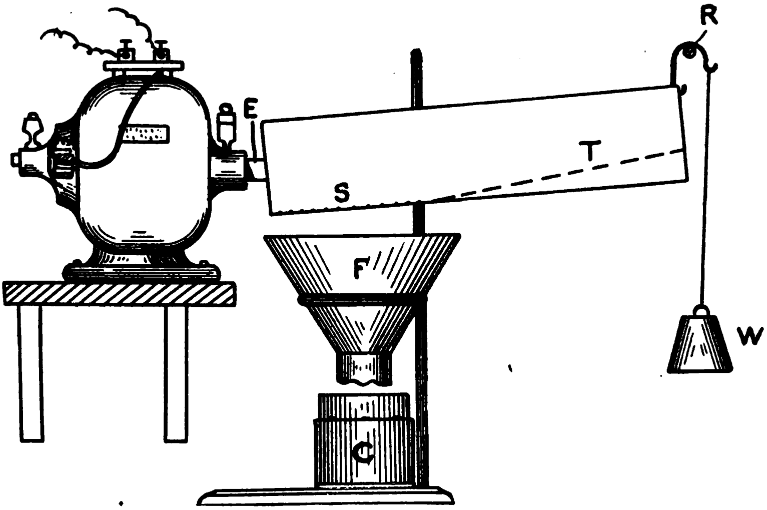

FIG. 27.—Apparatus for screening soils.

The apparatus finally used is shown in figure 27. To the shaft of an electric motor is fastened an eccentric *E*, made from a rod 2 centimeters in diameter, in which the shaft hole is drilled 0.5 centimeter off center. This eccentric fits into a hole in one end of the screen box *ST*. The motion of the revolving eccentric gives the screen a rapid shaking in both vertical and horizontal planes, which is very effective in forcing the damp soils through the mesh. The screen *S*, which is of 3 meshes to the centimeter, is in only one end of the box. A false bottom *T*, made of tin, serves to feed the material toward the mesh during shaking. The upper end of the box is supported by means of two hooks, resting on a horizontal rod *R*, shown in cross section in the figure. The hooks are made of heavy insulated electric-light wire, the covering of which serves to reduce the noise caused by rattling. Further, to prevent rattling at that end of the screen, a kilogram weight *W* is hung between the hooks. With this method of support the upper end of the screen is free to move, yet the motion is so reduced that during shaking the box stays well in position. The soil, after passing through the screen, falls into a funnel *F* and from there into the cup *C*, which holds the sample during the remainder of the experiment.

The cup proper is 12.5 centimeters in diameter and 9 centimeters high, having a capacity of 1,100 cubic centimeters. A rim is added, which makes it possible to fill the cup above its own level. The rim is then removed and the soil leveled off to the edge of the cup. This gives a more uniform packing in the upper layer of the soil.

The shaker makes it possible to repeat the packing of the same sample and also gives a basis of comparison in the measurements made on different samples, since the soil in each case is treated in the same way, falls through the same distance, and therefore is subjected to the same packing forces. Reproduction of these conditions is essential in a series of measurements made upon samples containing different quantities of water, where it is desirable that the only variable entering should be the water content.

PACKING APPARATUS.

The soil sample packed by the method just described is put into a uniform condition for experiment. Starting with the soil sample thus prepared it is possible to vary the packing in a definite and known way and thus study the effect of packing on the physical condition of the soil. The packing is done by the arrangement shown in figure 28, where a front and side elevation of the apparatus is shown. A vertical shaft of brass *AB* works easily through a wooden guide block *G*. On the bottom of the shaft is a circular plate *B* of hard rubber, just a little smaller than the inside of the cup *C*, into which it fits when packing the soil. On the upper end of the shaft is another plate *A*, which serves as a scale pan for the weights *W*, which are of lead and so made that they can be placed in the middle of *A* and concentric with one another, thus avoiding any serious side thrust where the rod passes through the guide. The shaft and plates are connected over pulleys with a weight *L*, by which they are balanced. In order to have the cup *C* still full after packing, a rim *R*, 4 centimeters high, is put on the cup. The screened soil is leveled to the upper edge of *R* and packed under any desired weight at a steady pressure for four minutes, after which the rim is removed and the soil surface reduced to the level of the cup proper. The sample is then ready for the penetration tests.

The behavior of the soil when packed in this way is indicated in figure 29, where a series of measurements for Podunk fine sandy loam containing 2.3 per cent water is shown. In addition to the packing caused by the soil falling from the screening machine, the soil was further compressed under pressure of 10, 30, and 50 grams per square centimeter. These pressures correspond to weights of 1, 3, and 5 kilos, the area of the compressing plate being about 100 square centimeters. The curve indicates that the increased packing pressure applied in this manner gives a fairly uniform increase in the force required for penetration.

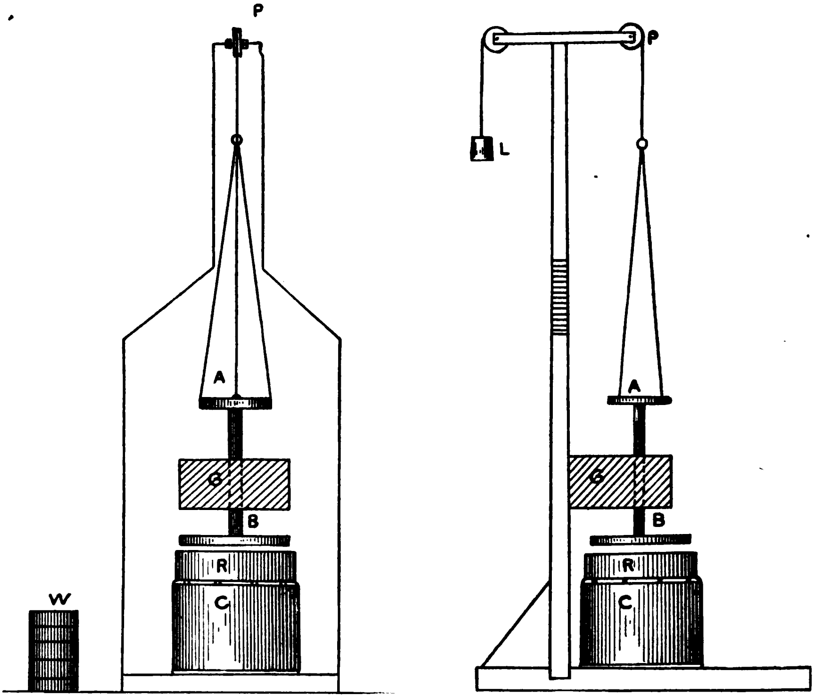

FIG. 28.—Apparatus for packing soils.

PENETRATION APPARATUS.

The force required for penetration was measured on the apparatus shown in figure 30. The penetrating tool *A* is made from a steel rod 1 centimeter in diameter. This is turned into the form of a cone 10.5 centimeters long and 1 centimeter in diameter in the thickest part. The large end of this cone terminates in a tongue which is so fastened to the scale beam *AB* that it is free to swing in the vertical plane of the beam. The beam itself, made of oak, is 140 centimeters long from the end *A* to *D*, the point of rotation. A counterweight *W* balances the beam and its attachments. Midway between *A* and *D* a pail *P* is hung, into which sand is run from a funnel *F* through a rubber tube closed by a pinchcock. This gives a method of constantly adding weight without jarring and of increasing the pressure to just the value necessary to force the tool into the soil to the required depth. The scale beam is guided beteween the upright parallel rods *G*, spaced to allow a free movement of the beam between them. M_1 and M_2 are clamps that check the up-and-down movement of the beam. The depth to which the point penetrates is determined by the position of M_2. The measurement is always begun at the same height—the level of the cup, which was also the soil level—and weight is added until the beam reaches M_2, by which time the tool has penetrated 6 centimeters into the soil. The approach of the beam to M_2 is observed by means of a small mirror *R* fastened at an angle to M_2.

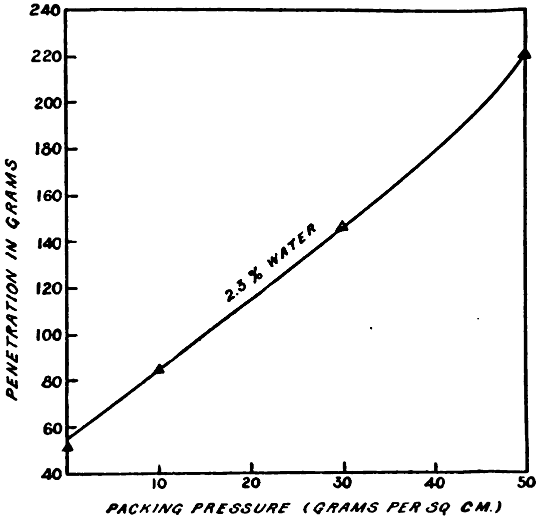

Fig. 29.—Penetration-packing results.

In making a penetration measurement the procedure is to make up a large soil sample to the desired water content, which is then determined accurately by drying a sample at 110° C. and calculating as per cent on the dry weight of soil. This method makes the different water contents of the same soil comparable one with another. The total sample is well mixed by screening and placed in a tightly covered pail. This holds enough soil to permit of repeating the measurements several times without twice using the same portion of soil. This is essential because a wet soil dries out quite rapidly when exposed to the open air, particularly during screening. By using a fresh portion each time successive measurements are made there will be but slight differences in the water content of the different samples. The soil is then leveled to the top rim by cutting off the extra material in such a way that no packing results, after which it is pressed, if desired, in the packing machine, the rim removed, and the soil again cut off to the level of the top of the cup. The penetration measurements are then made; generally three trials for each sample. They should be made at points the same distance from the rim of the vessel and equal distances apart. This condition is easily attained by drawing on the table a circle the size of the cup and eccentric to the point of the penetrating tool. The cup is so placed that it always coincides with this circle and between each measurement is rotated through 120 degrees. This method of spacing eliminates the personal factor of choosing the points for penetration and also makes the results more concordant. Since the soil in falling through the funnel of the shaking machine generally runs into the middle of the dish, from which point it spreads toward the sides, it tends to pack in the middle of the dish somewhat more closely than around the edges, so the packing at equal distances from the center is the same. After penetration the weight of the sand required to force the tool into the soil is determined. Since the pail is suspended in the middle of the beam, one-half the weight of the sand is the pressure applied in penetration. The cup and the soil are also weighed, the weight of the cup subtracted, and the specific gravity of the soil sample calculated from the volume of the cup.

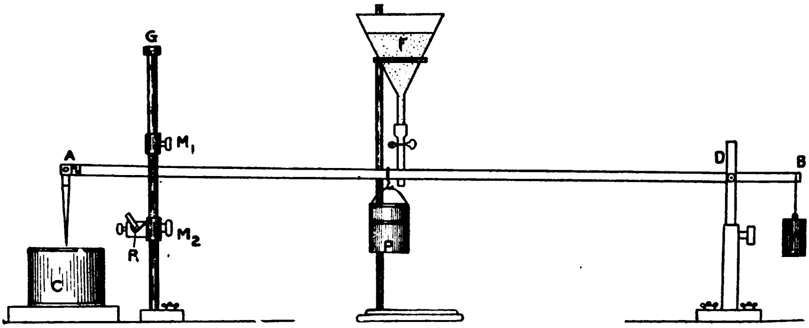

FIG. 30.—Apparatus for measuring penetration.

No difficulty is experienced in taking three penetration measurements on one dishful of soil. The three points at which the penetration tool enters the soil are far enough apart that the crowding aside of the soil at one point by the penetrating tool does not affect the following measurement at another point. Should it do so the force required for penetration would increase with each successive measurement, while as a matter of fact the variation is in no way regular between the different measurements.

APPARATUS FOR MEASURING VOLUME.

Preliminary method.

The first apparatus designed for volume measurements was not intended for very extended use, but rather as a convenient method of preliminary investigation. Some parts of it were used in subsequent investigations, and therefore a description of it is given here. The apparatus is illustrated in figure 31. The soil is contained in a glass tube *A*. For this purpose an Argand chimney has been found satisfactory and of suitable dimensions. In order to permit the wetting of the soil by capillarity the bottom of the tube *A* is closed by a ring *B*, made from a piece of brass tubing 2.5 centimeters long, with an inside diameter just a little larger than the outside diameter of the glass tube. A disk of brass gauze is soldered into the ring, as indicated in the diagram by the heavy dotted line. The ring is fastened to the tube by means of three set screws, one of which is indicated by *C*. In order to keep the finer soil particles from sifting through the brass gauze the end of the tube is covered by filter paper *D* before insertion into the ring. The dry soil is poured into the glass tube and then wetted by dipping the bottom of the container into water. Bearing on the upper surface of the soil is a brass tube *MN*, which works through a wooden guide block *E*. Changes in the volume of the soil cause, of course, a change in the level of the upper surface, and this change is communicated to the tube *MN*, and followed at *M* by a micrometer screw held firmly in place to the support of which *E* is a part. In order to hasten the drying the evaporation from the surface of the soil at *N* is increased by blowing a stream of air into the top of the tube. The air used for this purpose is passed through sulphuric acid in order to dry it. The drying progresses slowly owing to the small amount of surface exposed when *N* is in position. It is not feasible to remove *N* between measurements on account of the uncertainty of getting it back into the

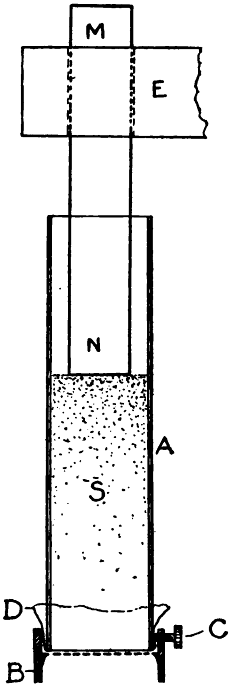

FIG. 31.—Apparatus for glass tube method of measuring changes in soil volumes.

same place when another measurement is to be made. As the drying occurs only at one end of the soil column an error is introduced, since the top of the soil was drier than the bottom. However, in a soil column of this length, if the drying proceeds slowly, this difference in moisture content of the top and the bottom is not very marked. More serious difficulty might be caused by the adhesion between the soil and surface of the glass, which would seriously cut down the influence of changing moisture content on the volume. It is evident from this preliminary attempt that a method suitable for accurate volume work should embody the following points: (1) In order to shorten the time required for carrying through one experiment it is essential that the drying out of the wet sample be rapid; this can be accomplished by exposing as great an area per unit volume of soil as possible. (2) The thickness of the soil from the drying surface down should be small in order that no large difference in moisture content may occur between the top and the bottom of the sample. (3) Since the change in volume is measured by the linear contraction it is essential to have the length in this one direction as great as possible. (4) The soil should be supported in such a way that after drying out it can be wetted again by capillarity without otherwise disturbing the sample, thus making it possible to use the same soil sample through several cycles of moisture change. (5) The soil sample should also be supported in such a way that it is independent of the measuring apparatus and movable at will, so that the same micrometer may be used to measure several samples drying out at the same time. These considerations led to the development of the "soil column method."

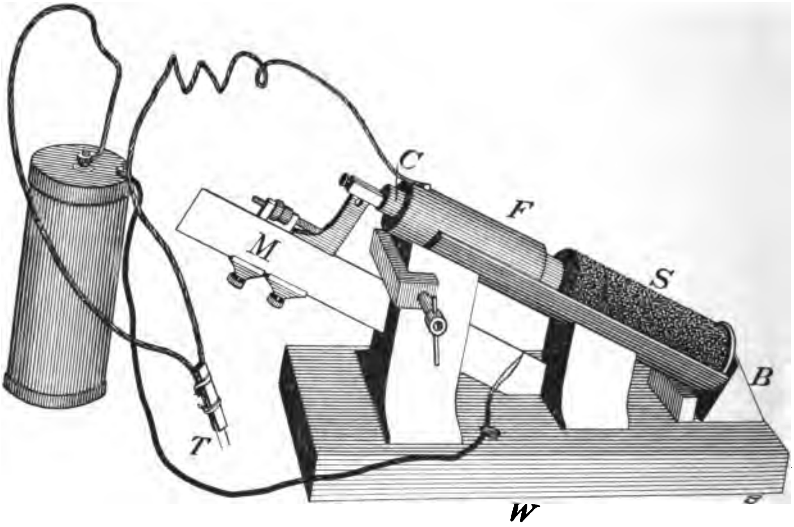

FIG. 32.—Apparatus for soil column method of measuring changes in soil volumes.

Soil column method.

The apparatus used in this method is shown in figure 32. The soil column *S* is molded in an apparatus similar to that shown in figure 31, where the soil is either put in dry and wetted by capillarity or packed into the tube in moderately moist condition, in which state it holds together well when pushed out of the tube onto the brass support shown in the figure. This support is made by cutting longitudinally a brass tube of a diameter a little larger than that of the soil column. Into one end of the support a circular brass disk is screwed so that it is perpendicular to the axis of the tube. Against this disk the lower end of the soil column rests. The disk is perforated so that a column can be wet by capillarity by simply dipping the lower end of its support into water, thus rewetting the sample without in any other way disturbing it. In this arrangement a large surface of soil is exposed to evaporation, and drying proceeds with considerable rapidity. A wet column of this kind reaches the air-dry condition in two to five days, depending on the nature of the soil. This method also insures a comparatively uniform moisture content from the top to the bottom of the sample. Resting against the upper end of the soil column is a brass follower *F* made from heavy brass tubing by inserting into the two ends pieces turned from solid brass. The part projecting from the lower end is made somewhat smaller than the tube so that it will not come in contact with the surface of the soil support, because upon contraction enough soil is left to roughen considerably this surface. The upper end contains a contact piece *C* turned from a brass rod. This is so arranged that by means of a screw, shown in the figure, it may be adjusted to lengthen or shorten the follower. By means of this adjustment the total length of the soil column and the follower can be made nearly the same in different samples, thus adapting the limits of the micrometer screw to their measurement. The Vernier scale and micrometer screw are shown at *M*. As the soil contracts during the wetting, the inclination of the support and the weight of the follower are sufficient to keep it pressed down against the end disk. The contraction of the soil therefore results in a downward movement, which is measured by the micrometer. In order to tell just when the micrometer comes in contact with the end of the follower at *C* an electrical contact device is used. One terminal of a battery is connected through an electric bell to *F*. When *M* makes the metallic connection at *C*, the circuit is closed and the bell rings. Instead of the bell the figure shows an arrangement *T* in which the two bare terminals are held at a short distance apart. By placing these two wires on the tongue, the instant of contact at *C* may be detected by a sharp acrid taste. This device is even more delicate and satisfactory than the bell. The contact can be determined with such precision that the readings taken at the same time show no variation within the limits of the micrometer used. The micrometer scale is held firmly in place by means of a screw clamp. The wooden support is sawed in such a way that the micrometer scale is slipped into position and a screw clamp pinches the two sections of the wooden support. The part of the apparatus consisting of the soil column and its follower can be lifted from the wooden supports without in any way affecting the soil sample. A different soil sample can be placed in position and measured by the same micrometer. At each measurement this movable part comes into the same position, for it is brought down firmly against the end block *B*. Since the wooden vertical supports are cut V shaped, the half-round section of brass tubing fits snugly into place.

This method has proved well suited to soils having the power to retain the form of the cylindrical soil column irrespective of the moisture content. Some soils, however, can not be successfully handled in this way, either because when wet they become incoherent and do not retain their form or because when dry they crumble. The method is not well suited for continued observations on wetting and drying of the same soil sample, because, as has been pointed out in a previous chapter, the volume changes tend to cause cracking of the soil; these cracks become points of weakness and in time cause the breaking down of the soil column.

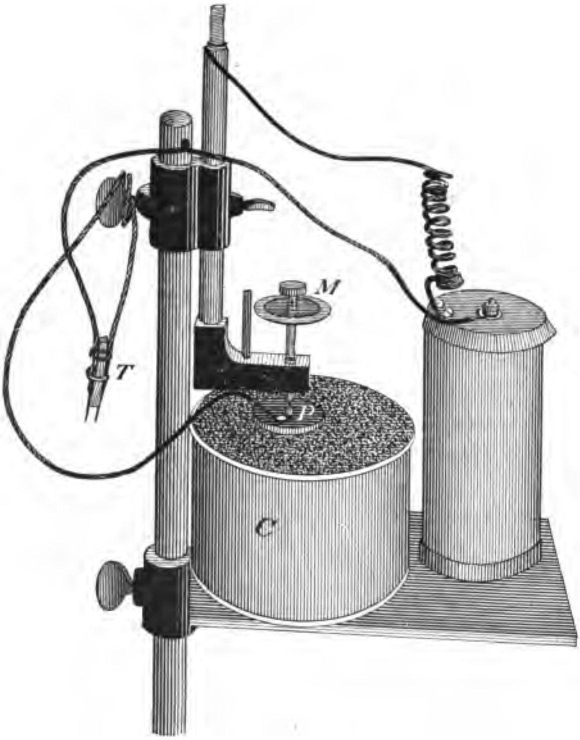

FIG. 33.—Apparatus for micrometer method of measuring changes in soil volumes.

Micrometer method.

In order to get around the difficulties just described the "micrometer method" was devised, in which the soil sample is better supported, being held in a cup. The form of apparatus is shown in figure 33. The soil sample is contained in a cup *C*, which has a perforated bottom through which the soil may be wetted. This cup rests directly on the metal table of an adjustable stand, to which the micrometer screw is also attached. This method of support has a distinct advantage, since there is little possibility of the table and micrometer changing their relative positions and thus affecting the results. The variation in the height of the soil surface is measured by means of the micrometer screw *M*. A brass plate *P* with a projecting short vertical shaft rests on the surface of the soil. The micrometer point is brought just into contact with the top of the shaft. The contact is determined in the same manner as described in the preceding method. In order to obtain a good electrical contact with the plate *P* without disturbing its position in any way, a drop of mercury is held in a depression drilled into the surface of the brass.

This method also permits measurements being made on a number of samples, since the cup *C* can be removed from the table and another cup inserted in its place without displacing the micrometer. The moisture content of the soil sample corresponding to the time of measurement is determined in both this and the soil column method by directly weighing the supporting dish, the dry soil equivalent being determined when the sample is first prepared. Although the micrometer screw used in this method measures to 0.0001 centimeter, measurements were ordinarily made only to 0.001. On account of the electrical conductivity of the moist soil and since the cup rests on the metallic table it is necessary to insulate the brass plate *P* from the soil. This is done by fastening a hard rubber disk to the underside of the plate. The same result can, of course, be obtained by insulating the cup *C* from the stand. In this method the amount of surface exposed to evaporation is not so large as in the soil column method, so that the time required for a series of measurements is somewhat longer. Because of the better support of the soil column this method is applicable to almost any soil and quite independent of errors due to a defective soil column. In any future work it would be well to use larger dishes; this would tend to reduce to a minimum any errors due to adhesion between the soil and the cup. A deeper dish may profitably be used, thus giving a larger linear change, but it must be not deep enough to cause a large difference in moisture content between the lower and upper soil layers.

Cathetometer method.

The cathetometer method closely resembles the micrometer method. The soil is contained in a similar dish and the up and down movements of a point fastened to a brass disk are measured by means of a cathetometer instead of a micrometer. This method is valuable as a check method, showing that the same results are obtained irrespective of the method used. It offers no particular advantage over the micrometer method and possesses some disadvantages. Since the cathetometer and the soil are placed several feet apart, they have no support in common, and a change of pressure on the floor may cause a variation in the level and a corresponding error in the readings obtained. Sighting the cross hairs of the cathetometer telescope on the point does not permit the same accuracy of reading as in case of the micrometer with the electric contact method. The finest graduations on the cathetometer used were 0.01 centimeter. This, added to the difficulty of reading mentioned above, made very accurate results impossible. This method might be improved by having the apparatus set up on a firm foundation, having better sighting device, larger dishes, etc., but the only advantage it can then offer over the micrometer method is that the plate on the soil surface would not be subject to any disturbing external pressure, such as might possibly be caused by the micrometer screw.

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Forestry
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LETTER OF TRANSMITTAL

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., January 14, 1908.

Sir: I have the honor to transmit the manuscript of a technical article entitled "Absorption of Vapors and Gases by Soils," by Messrs. Harrison E. Patten and Francis E. Gallagher. It contains a historical review of the subject, together with experimental studies on the conditions which determine the quantity and rate of gaseous absorption by soils.

The article gives much valuable information which should be made available to the public. In accordance with your suggestion it has been gone over carefully with Assistant Secretary Hays, who authorizes me to state that he concurs in my recommendation for its publication.

Respectfully,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

PREFACE.

In the continuation of the studies on absorption which have been carried on in this Bureau, it has been deemed desirable to direct attention especially to the absorption of gases by soils, and the present bulletin contains a description of certain special studies on this subject by Messrs. Patten and Gallagher.

That soils have a high absorptive power for gases, and show a direct selective absorption from gas mixtures as well as from liquid solutions, has long been known, and this fact has generally been recognized as having an important agricultural and geological significance. But up to the present it can not be said that agricultural investigators have given the question the consideration which its practical importance warrants.

In the present bulletin the absorption of the principal gases by various types of soils and the rate at which such absorption takes place have been brought out in such a manner that practical workers in soil problems will be able to use the results to advantage. Special significance must be attached to the absorption of water vapor, and in this bulletin the principal facts now known from the investigations of former workers or of the authors of the bulletin themselves are brought together in such shape that they are available not only for practical workers, but for the further investigation of scientific workers.

The relation between the absorption of water vapor on the one hand and the evaporation of water from that soil has been carefully investigated, and the laws controlling it have been clearly brought out; and the influence of soluble materials contained in the soil as affecting these laws has been shown. The significance of cultural methods as affecting either the absorption of water vapor or its evaporation has been shown. And finally, the important practical fact has been established that the wilting point—or that water content of the soil at which plants can no longer thrive and which has been shown elsewhere to be a physical factor of the soil—marks a water content higher than that which the soil can attain by direct absorption from a humid atmosphere, even though this latter be maintained at the point of saturation.

The laws governing the absorption of other gases or vapors appear in general to be very similar to those governing the absorption of water vapor, and it may now be safely claimed that the broad subject of absorption of vapors by soils has been brought to a satisfactory state as regards not only our theoretical knowledge of the principles involved and their importance to practical agriculture, but also as they bear upon the practical methods of control.

FRANK K. CAMERON.

CONTENTS.

Page.

Previous work 9
  Introduction 9
  Absorption of gases 9
    Absorption of air 10
  Absorption of water vapor by soils 10
Absorption of water vapor 14
  Statement of the problem 14
  Evaporation studies 15
    Experimental methods 15
    Diffusion constant for desiccators 15
    Experimental data 15
    Discussion 19
  Absorption studies 21
    Experimental data 21
    Discussion 22
  Dependence of moisture content upon humidity 22
Absorption of other vapors 24
Absorption of gases 25
  Absorption of air 25
  Absorption of oxygen 26
  Absorption of nitrogen 27
  Absorption of carbon dioxide 27
  Absorption of ammonia 29
  Absorption of hydrogen 30
Effect of temperature upon absorption 31
  Theoretical considerations 31
  Experimental data and discussion 32
Absorption capacity 35
Distribution 38
Rate of absorption 40

Determining factors:

    Chemical composition 40
    Physical condition 40
    Viscosity of the vapor 40
    Absorption capacity 40
    Partial pressure, or humidity 41
    Previously absorbed vapor 42
    Temperature 43
Rate of evaporation 43
Energy changes 46
Summary 48

ILLUSTRATIONS.

FIGURES.

Page
FIG. 1. Curves for quartz flour, showing effect of humidity upon rate of evaporation 16
2. Curves for Podunk soil, showing effect of humidity upon rate of evaporation 17
3. Curves for Sea Island cotton soil, showing effect of humidity upon rate of evaporation 19
4. Drawing of desiccator containing soil sample 20
5. Curve showing variation of moisture in quartz flour with increase in atmospheric humidity 22
6. Curve showing variation of moisture in Podunk soil with increase in atmospheric humidity 22
7. Curve showing variation of moisture in Sea Island cotton soil with increase in atmospheric humidity 22
8. Curve showing variation of moisture in humus with increase in atmospheric humidity 23
9. Curves showing vapor pressure of water, and of moist soils at various temperatures for case I, assuming that absorption increases with rise in temperature 30
10. Curves showing vapor pressure of water, and of moist soils at various temperatures for case II, assuming that absorption decreases with rise in temperature 31
11. Curve showing decrease in absorption of water vapor by quartz flour with rise in temperature 32
12. Curve showing decrease in absorption of water vapor by Podunk soil with rise in temperature 33
13. Diagram of apparatus used to determine absorption of water vapor by soil at the boiling point of water 34
14. Curve showing decrease of absorption of water vapor by Sea Island cotton soil with rise in temperature 34
15. Curves showing rate of absorption of water vapor by Sea Island cotton soil under different degrees of humidity 41
16. Curve showing rate of evaporation of water from Podunk soil 43
17. Curve showing rate of evaporation of water from Miami soil 44
18. Curve showing rate of evaporation of water from Leonardtown soil ... 44
19. Curve showing rate of evaporation of water from muck soil 45

ABSORPTION OF VAPORS AND GASES BY SOILS.

PREVIOUS WORK.

INTRODUCTION.

It is well known that charcoal absorbs enormous volumes of gases from putrefying animal matter, and the similar power of soils to take up odors from excreta has been utilized from the earliest times.

The term *absorption* includes adsorption upon the surface, possible penetration of vapor into the solid, and retention of liquid in the angles formed between adjoining particles. A short review of the development of our knowledge of gaseous absorption is helpful here in bringing to mind the experimental facts and the varying explanations offered in connection therewith.

ABSORPTION OF GASES.

Fontana in 1777 established the fact that numerous porous bodies retain gases upon their internal surface, but did not deduce regularities from his data.

Morozzo, Rouppe, and Norden[a] confirmed his observations in 1800, but de Saussure,[b] during 1812 to 1814, was the first to investigate this field extensively. He heated his absorbent material to redness before using, to expel residual gases, and then subjected the weighed absorbent to the action of a gas, under known temperature and pressure conditions. He drew the following conclusions: (1) The porous bodies investigated absorb gases; (2) the degree of absorption varies with the form and magnitude of the pores; (3) different substances possess a different absorption capacity; (4) the same substance absorbs different quantities of different gases; (5) easily condensed gases are in general absorbed more easily; (6) absorption decreases as temperature increases; (7) at higher pressure more gas is absorbed than at lower pressure; (8) heat is evolved during the process of absorption.

To these fundamental observations Smith[c] adds: (1) Charcoal exercises a selective absorption toward mixtures of gases; for a considerable time oxygen alone is absorbed from air; (2) charcoal saturated with nitrogen and then placed in other gases first gives up a part of the nitrogen before absorbing the second gas; (3) charcoal saturated with oxygen does not give up the gas, either upon warming or treatment with boiling water, but under these conditions carbon dioxide is evolved rather than oxygen.

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[a] O. Lehmann, Molekular-physik, II part, 83.

[b] Ann. Phys. Gilbert, **47**, 113 (1814).

[c] Ann. Chem., Suppl. **2**, 262 (1862-1863).

Stenhouse,[a] too, has studied the absorption of gases by charcoal made from various materials; his figures, given in Table I, represent the number of cubic centimeters of gas absorbed by 1 gram of charcoal. Wood charcoal shows a higher absorption for the gases used than does peat or animal charcoal, with the exception of hydrochloric acid gas, which is taken up in greater volume by peat.

TABLE I.—*Absorption of gases by charcoal, according to Stenhouse.*

Gas.	Kind of charcoal.		
	Wood.	Peat.	Animal.
	C. c.	*C. c.*	*C. c.*
Ammonia	98.5	96.0	43.5
Hydrochloric acid	45.0	60.0	....
Sulphurous	32.5	27.5	17.5
Carbonic acid	14.0	10.0	5.0
Oxygen	0.8	0.6	0.5

Dewar[b] has found that charcoal and lampblack are nearly equal in absorbing power for gases at the temperature of liquid air, and that graphite is only one-fourth as good an absorbent.

ABSORPTION OF AIR.

Reichardt and Blumtritt[c] showed that nitrogen is absorbed to a much greater extent by soils and soil constitutents than is oxygen and that each gas is retained to a different degree by different substances—a clear indication of the selective power which solids and gases mutually exert in absorption reactions.

ABSORPTION OF WATER VAPOR BY SOILS.

When a soil is saturated with water by rain, part of the water percolates away to lower levels, and another part of the water evaporates from the surface.

With a view to correlating the capacity of soils to resist drying out, with their composition and with their productiveness, Schübler[d] determined the water vapor absorbed by various soils and soil constitutents from a nearly saturated atmosphere during 24 hours. This absorption process is evidently the reverse of drying out, but gives a measure of the speed with which a dry soil takes up the first portions of water vapor, and this speed is clearly an indication of the strength with which the water is held by each soil. Thus, he found that 1,000 parts of soil absorbed parts of water as follows: Quartz sand, coarse, 0; gypsum, 1; calcareous sand, 3; plow land, 23; clay soil (60 per cent clay), 28; slaty marl, 33; loam, 35; fine carbonate of lime, 35; heavy clay soil (80 per cent clay), 41; garden mold (7 per cent humus), 52; pure clay, 49; carbonate of magnesia (fine powder), 82; humus, 120.

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[a] Cited by Johnson, How Crops Feed, p. 160.

[b] Chem. News, **94**, 174 (1906); Proc. Roy. Soc., **74**, 130 (1904).

[c] Jour. prakt. Chem., **98**, 476 (1866).

[d] Cited by Johnson, How Crops Feed, pp. 161–162, 1870.

Similarly Davy[a] gives the quantity of moisture taken up during one hour exposure to the air by soils which had been dried at 212° F. as follows, in parts of water per 1,000 parts of soil: Sterile soil of Bagshot heath, 3; coarse sand, 8; fine sand, 11; soil from Mercy, Essex, 13; very fertile alluvium, Somersetshire, 16; extremely fertile soil of Ormiston, East Lothian, 18.

From these results it may be concluded that the absorptive capacity of soil for water vapor is generally higher the finer the texture of the soil and the greater its content of humus. It appears, too, that productive soils have a very considerable capacity for water vapor, while the poor soils range much lower.

Regarding the effect of temperature upon the quantity of water vapor absorbed, Knop[a] has shown that at higher temperature the absorption is very considerably decreased. A sandy soil from Moeckern, Saxony, absorbed in parts of water per 1,000 parts of soil the following quantities of moisture: At 55° F., 13; at 66°, 11.9; at 77°, 10.2; at 88°, 8.7.

The experiments of Ammon[b] likewise show that the absorption of water vapor by soil constituents decreases as the temperature rises. The relative absorption at any one temperature of the substances used decreases in the order, ferric hydroxide, humus, kaolin, calcium carbonate, gypsum.

Von Dobeneck[c] has studied in great detail the conditions which determine the absorption of water vapor and gases in general by various soil constituents and admixtures of the same, with the following results: (1) The absorption is greater the finer the particles of the solid; but this increase is not directly proportional to the increase in surface, since large grains absorb relatively more gas than would be expected from the surface exposed. It should be remembered, however, that great error is introduced when the surface of a powder is calculated from the average diameter of its granules. (2) He found that adsorption and hygroscopic retention of moisture upon surfaces, which were then looked upon as different, are subject to the same controlling conditions. (3) The different soil constituents all possess a considerable absorption capacity, but gases are absorbed to a different degree by each solid substance. (4) Mixtures of these soil constituents absorb gases additively; that is, each soil material exerts its absorptive effect independently of the rest of the soil about it. (5) Absorption decreases with rise in temperature and is very nearly proportional to the reciprocal of the partial pressure. (6) For atmospheres of the same relative humidity, the temperature has little effect upon the mass of water absorbed; the absorption increases with increasing relative humidity, and at 20° C. the rise in absorption for equal per cent increments in the relative humidity is greater the nearer the interval lies to the point of saturation (100 per cent humidity). (7) Soil constituents moistened with water absorb gases in greater quantity than the same mass of water alone.

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[a] Cited by Johnson, How Crops Feed, pp. 161–162, 1870.

[b] Forsch. Agr.-Phys., **2**, 36 (1879).

[c] Forsch. Agr.-Phys., **15**, 163 (1892).

Van Bemmelen[a] has determined the absorption of water vapor by soils and inorganic oxides, especially such as yield gelatinous hydrates with water, with reference to (1) the influence of original water contained in the soil or solid oxide upon the quantity of water it can yet absorb; (2) the effect of vapor pressure upon absorption and liberation of moisture; (3) the structure and history of the oxide as related to its absorptive power. He used the oxides, SiO_2, SnO_2, MnO_2, Al_2O_3, Fe_2O_3, Cr_2O_3, BeO, MgO, and CuO and various soils. His results in general indicate that the absorption of water vapor increases with the vapor pressure, but is not simply proportional to it; that the fineness of the grains of a partially hydrated oxide has little influence upon its absorption—an effect to be expected where imbibition takes place; that the moist oxides expand as more water is absorbed and contract as this water evaporates from them in an atmosphere of lower vapor pressure; that some oxides form a translucent jelly when they contain a certain quantity of water, and this translucence indicates that the jelly is made up of fine cells. He concludes that the existence of definite chemical hydrates in these noncrystalline jellies is as yet undemonstrated and extremely improbable.

Van Bemmelen's reason for so thoroughly investigating these gelatinous inorganic hydrates is that much of the absorptive power of a soil is due to their presence, occasioned by the disintegration of minerals subject to weathering. His results on the absorption of water vapor by soils are similar to those obtained with these inorganic oxides, and agree in general with the results of earlier investigators. Each soil shows its own peculiar power of absorbing water vapor—the finer the soil grains the greater the absorption; the presence of individual soil constituents of high absorptive power, of course, raises the absorption in proportion to the amount of each in the soil.

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[a] Zeit. anorg. Chem., **5**, 467 (1893); Ber. deutsch. chem. Ges., **13**, 1467 (1880); Jour. prakt. Chem., **23**, 324, 379 (1881); **26**, 227 (1882); Rec. Trav. Chim. Pays.-Bas, **7**, 1 (1888); Jour. prakt. Chem., **46**, 497 (1892); Zeit. anorg. Chem., **18**, 122 (1898); **20**, 185 (1899); **23**, 111–321 (1900); Sitzungsber. d. K. Akad. d. Wiss., Amsterdam, Nov. 26, 1902; Arch. Néel. (2), **10**, 267 (1906). See also Cross, On the Reformation of Hydrates, Jahresb., 1879, 179; also, Spring and Lucion, Zeit. anorg. Chem., **2**, 195 (1892).

According to Hilgard,[a] the hygroscopic moisture of a soil may vary from 2.48 per cent to 21 per cent, depending upon its composition. He has criticized the experiments of Schübler, Knop, and others, who found that absorption of water vapor decreases with rise in temperature. Hilgard finds that exactly the reverse is the case; soils exposed to an atmosphere saturated with water vapor absorb more moisture at high temperature than at low.

An attempt to discriminate between moisture held by a powder as "hygroscopic moisture" and water in the capillary spaces meets with difficulty.[b] We have no sharp experimental method of ascertaining what fraction of the water is retained on the surfaces of the grains. This is especially so as an even distribution of moisture throughout the powder is hard to secure, and failing of this the powder is balled together and holds part of the liquid in its capillary spaces between the grains.

Briggs[c] determined the quantity of water vapor absorbed by quartz grains of various degrees of fineness, and from the mechanical analysis of each powder calculated the surface presented, and thus found the thickness of the layer of adsorbed water. Assuming the density of the film as uniform and equal to unity and postulating an even distribution of the water over the entire surface, the maximum thickness obtained was 2.66×10^{-6} cm. in an atmosphere within 1 per cent of saturation at 30° C. He concludes that the adsorption is not due to soluble bodies present upon the surface of the quartz, as Warburg and Ihmori have suggested, but to the mutual attraction of quartz and water.

Parks[d] calculates the thickness of the water film upon glass wool as 13.3×10^{-6} at 15° C. Trouton[e] and O. Masson and E. S. Richards[f] have carefully determined the conditions under which cotton absorbs moisture. Trouton suggests that the water vapor is condensed to liquid upon the surface of the cotton. Masson and Richards find that cotton containing a definite proportion of moisture resembles an aqueous solution in that it exercises a vapor pressure which is at different temperatures a constant fraction of that of pure water.

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[a] "Soils," pp. 196, 198 (1906).

[b] Soyaka, Forsch. Agr.-Phys., 8, 1 (1885); Whitney, Agricultural Science, **3**, 199 (1889); Katao, Ueber die Wasserbewegung in Boden, Bul. Col. Agr., Imp. Univ. Tokyo, Vol. 3, No. 1 (1897); Briggs, Bul. No. 10, U. S. Dept. of Agr., Division of Soils (1897).

[c] Jour. Phys. Chem., **9**, 617 (1905).

[d] Phil. Mag. (6) **5**, 519 (1903); also (6) **4**, 240 (1902).

[e] Proc. Roy. Soc. London, **77**, Ser. A, 292 (1906).

[f] Ibid., **78**, Ser. A, 412–429 (1906).

In this connection it is interesting to note that Bunsen [a] found that glass fiber continued to give up moisture on heating until a temperature of 503° C. was reached; similarly, Day and Allen [b] state that a temperature of 600° to 800° C. (a low red heat) is required to remove hygroscopic moisture from minerals. From the fact that moisture is retained upon the surface of these substances at high temperature it may be inferred that the attraction between the substance and water is greater than the vapor pressure, which at such temperatures amounts to hundreds of atmospheres.

ABSORPTION OF WATER VAPOR.

STATEMENT OF THE PROBLEM.

The general problem before us is to find the relation of climatic humidity to soils. In nature a system is rarely in a state of equilibrium, and more or less rapid changes in the distribution of the constituents are in progress. Still, in the present instance, definite laboratory conditions for the equilibrium between soil moisture and water vapor in the air above it will afford a very fair approximation to field conditions, and by taking measurements upon the rate of approach to equilibrium we also secure an insight into the nature and rate of change in soil moisture during evaporation or absorption when sudden climatic changes disturb the approximate equilibrium between atmospheric moisture and soil moisture. Such displacement of equilibrium may be due to currents of air bringing a more or less humid atmosphere from a distance, or to heat changes accompanied by precipitation on cooling, or greater saturation capacity of the air for water on heating.

The first variation—change in humidity—may be experimentally reproduced by placing several equal portions of a soil of known moisture content in desiccators whose individual atmospheric humidity is maintained practically constant by sulphuric acid, differing in strength for each desiccator and thus giving a range of humidity from the very low partial pressure of concentrated acid to the vapor pressure of water at the temperature chosen for the experiments.

The second source of variation—heat changes—may be studied by running equilibrium experiments similar to those just described, but at different temperatures, and comparing the quantities of moisture in soil and in vapor above it at each of these temperatures.

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[a] Ann. Phys., **24**, 321 (1885).

[b] Pub. Carnegie Inst. of Washington, No. 31, pp. 56-57; Am. Jour. Sci. (4), **19**, 93 (1905).

EVAPORATION STUDIES.

Experimental methods.

The evaporation of water from soils was determined under different degrees of humidity, secured by maintaining the soils in small weighing bottles in desiccators containing sulphuric acid in varying concentration. Quantitative preliminary work showed the need of accurate temperature control; consequently the experiments here described were carried out in a double-walled air thermostat heated by incandescent electric lights, the current being controlled by a Geer thermo-regulator [a] and the air circulated by an electric fan. (The temperature was recorded, when desired, by a thermograph. The temperature could thus be held constant and within 0.1° C. for days.)

Diffusion constant for the desiccators.

As regards the diffusion of water vapor from the soil in the weighing bottle through the atmosphere of the desiccator down to the surface of the sulphuric acid, it may be stated that in general this takes place at a very constant rate. This constancy will be evident from an inspection of the curves given in figures 1, 2, and 3, for the evaporation of soils in atmospheres of different degrees of humidity. As may be expected, these curves are linear during the time when evaporation is taking place from the larger soil tubes, but when the soil moisture begins to evaporate from the finer capillary spaces, the rate of evaporation, and consequently the diffusion constant itself, changes as evaporation proceeds. A variation in the value of this diffusion constant may also be due to a slight difference in the size of the mouths of the weighing bottles.

Experimental data.

The rate of approach to equilibrium of quartz flour, Podunk fine sandy loam, and Sea Island cotton soils over water and over sulphuric acid of different strengths at 25° C. is given in Tables II, III, and IV, respectively. The upper section of each table shows the loss of water from a wet soil as the evaporation proceeds, while the lower section gives the absorption by the same soil in dry condition under the same conditions of temperature and humidity. Thus if sufficient time be given, the same percentage of moisture will be found in the soil regardless of its previous moisture content; i. e., equilibrium is approached from both the wet side and the dry side. At the head of each column in the tables is given the strength of sulphuric acid expressed in percentage by weight and the corresponding partial pressure of water vapor in millimeters of mercury.[b] The evaporation data from the upper half of Tables II, III, and IV are plotted in figures 1, 2, and 3, for quartz, Podunk, and Sea Island soils, respectively, ordinates being percentage moisture in the soil reckoned upon its dry weight, and abscissas time in days.

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[a] Jour. Phys. Chem., 6, 85 (1902).

[b] Landolt and Börnstein, Tabellen.

TABLE II.—*Change in moisture content of quartz flour exposed to atmospheres of different humidity at 25° C.*

MOIST SOIL.

Strength of sulphuric acid, with equivalent partial pressure of water vapor.								Water alone.	
94 per cent = 0.10 mm.		55.4 per cent = 6.0 mm.		42.55 per cent = 12 mm.		29.84 per cent = 17.9 mm.		23.55 mm.	
Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.
Days.	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*
0.00	30.00	0.00	30.00	0.00	30.00	0.00	30.00	0.00	30.0
.167	29.40	1.02	27.80	1.04	28.50	1.04	29.20	1.01	29.9
1.00	26.30	2.11	25.40	2.10	27.20	2.11	28.50	2.11	29.8
2.08	23.10	3.08	23.40	3.08	25.80	3.09	27.80	3.04	29.7
3.08	19.80	4.00	21.60	4.04	24.60	4.04	27.20	6.04	29.5
4.00	16.80	8.00	13.90	8.00	20.00	8.00	24.80	13.00	29.3
5.15	13.40	10.10	9.80	13.00	13.80	13.00	22.00	27.00	28.6
6.04	9.80	13.00	4.10	17.00	9.50	21.20	17.70	55.00	28.5
8.02	4.40	17.00	.10	19.20	6.90	23.00	14.30	97.00	25.4
9.05	1.90	33.00	.09	23.00	2.80	33.00	11.00		
9.87	.50			25.00	1.20	38.00	8.20		
10.13	.10			26.00	.20	46.00	4.30		
11.16	.10			27.00	.12	52.00	1.30		
17.00	.07			30.00	.12	97.00	.12		
33.00	.07			33.00	.11				

DRY SOIL.

0.0	0.10	0.0	0.1	0.0	0.10	0.0	0.10	0.0	0.10
1.0	.10	1.0	.1	1.0	.10	1.0	.10	1.0	.20
13.0	.08	33.0	.1	33.0	.11	3.0	.10	2.0	.20
33.0	.07					97.0	.12	3.0	.20
								6.0	.30
								13.0	.30
								27.0	.40
								55.0	.42
								97.0	.61

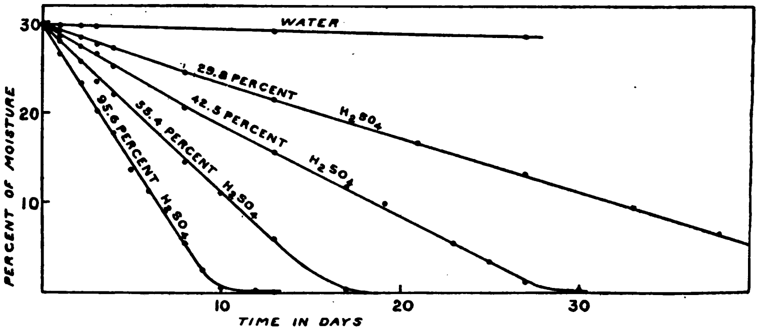

FIG. 1.—Curves for quartz flour, showing effect of humidity upon rate of evaporation.

TABLE III.—*Change in moisture content of Podunk fine sandy loam soil exposed to atmospheres of different humidity at 25° C.*

MOIST SOIL.

Strength of sulphuric acid, with equivalent partial pressure of water vapor.								Water alone.	
95.6 per cent =0.10 mm.		55.4 per cent =6.0 mm.		42.55 per cent =12 mm.		29.84 per cent =17.9 mm.		23.55 mm.	
Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.
Days.	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*
0.00	30.00	0.00	30.0	0.00	30.00	0.00	30.00	0.00	30.0
.167	29.50	1.02	28.1	1.04	28.70	1.04	29.20	1.01	29.9
1.00	26.70	2.11	25.9	2.11	27.50	2.11	28.50	2.12	29.8
2.09	23.30	3.08	23.8	3.09	26.80	3.11	27.80	3.12	29.7
3.00	20.30	4.00	22.1	4.04	25.20	4.04	27.20	6.04	29.5
4.00	17.90	8.00	14.8	8.00	20.60	8.00	24.60	13.00	29.2
5.15	13.90	9.10	11.2	13.00	15.70	13.00	21.60	27.00	28.6
6.04	11.50	13.00	6.0	17.00	11.90	21.20	16.80	55.00	27.5
8.02	5.60	17.00	.4	19.20	9.80	23.00	13.30	97.00	26.5
9.05	2.50	33.00	.3	23.00	5.70	33.00	9.70		
9.87	.70			25.00	3.50	38.00	6.50		
10.13	.40			27.00	1.10	46.00	2.50		
11.16	.30			30.00	.40	52.00	.60		
17.00	.13			33.00	.43	97.00	.51		
33.00	.04								

DRY SOIL.

0.0	0.30	0.0	0.3	0.0	0.3	0.0	0.30	1.01	0.30
1.0	.30	1.0	.4	1.0	.4	1.0	.50	2.12	.70
13.0	.16	10.0	.4	33.0	.4	3.0	.51	3.12	.70
17.0	.13	33.0	.3			97.0	.48	6.04	.80
21.0	.03							13.00	.90
33.0	.02							27.00	1.00
								55.00	1.10
								97.00	1.16
									1.24

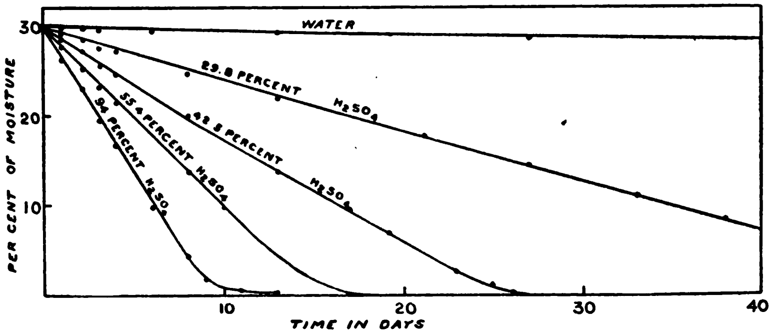

FIG. 2.—Curves for Podunk soil, showing effect of humidity upon rate of evaporation.

TABLE IV.—*Change in moisture content of Sea Island cotton soil exposed to atmospheres of different humidity at 25° C.*

MOIST SOIL.

Strength of sulphuric acid, with equivalent partial pressure of water vapor.								Water alone.	
94 per cent =0.10 mm.		55.4 per cent =6.0 mm.		42.55 per cent =12 mm.		29.84 per cent =17.9 mm.		23.55 mm.	
Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.	Period.	Moisture content.
Days.	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*
0.00	55.00	0.00	55.0	0.00	55.0	0.00	55.00	0.00	55.0
.167	54.20	1.01	52.9	1.04	53.2	1.03	54.10	1.10	54.8
.96	51.60	2.10	50.5	2.09	51.4	2.11	53.30	2.11	54.7
2.08	48.60	3.08	48.4	3.08	49.8	3.09	52.10	3.14	54.6
3.08	45.60	4.00	46.5	4.04	48.3	4.04	51.90	6.04	54.3
4.00	43.20	8.00	37.4	8.00	42.1	8.00	49.30	8.00	54.0
5.15	40.10	10.10	33.1	13.00	35.0	13.00	46.30	10.10	53.9
6.04	37.50	13.00	27.6	17.00	29.4	21.20	41.20	13.00	53.7
8.02	30.00	17.00	17.6	19.20	26.1	27.00	37.70	27.00	53.1
9.05	27.00	19.20	11.2	23.00	20.4	33.00	34.10	55.00	49.2
9.87	24.00	23.00	4.6	27.00	15.0	46.00	25.50	97.00	48.5
11.16	17.90	25.00	3.5	30.00	10.5	52.00	21.52		
12.08	13.70	27.00	3.1	33.00	6.6	97.00	6.08		
13.05	9.20	30.00	2.9	38.00	4.7				
14.00	6.40	33.00	2.9	46.00	4.4				
17.00	2.10	52.00	2.8	52.00	4.2				
21.00	.98								
33.00	.34								

DRY SOIL.

0.0	4.40	0.0	4.4	0.0	4.4	0.0	4.4	0.00	4.4
1.0	4.10	1.0	4.6	1.0	4.7	1.0	4.9	1.01	5.1
13.0	2.90	13.0	4.8	13.0	4.9	3.0	5.4	2.13	5.6
17.0	1.70	33.0	2.9	21.0	4.1	4.0	5.5	3.12	5.9
21.0	1.00	52.0	2.8			13.0	5.9	4.04	6.1
33.0	.47					21.0	6.0	6.00	6.6
						97.0	5.6	8.00	6.8
								10.10	7.2
								13.00	7.6
								27.00	8.6
								55.00	9.2
								97.00	9.7

Discussion.

Evaporation from soils under different conditions of humidity in general proceeds regularly, as shown by the above curves, which are similar in form. The curves for Sea Island soil over 55.4 per cent sulphuric acid and over the concentrated acid (fig. 3) are displaced to the left in their lower portions. This effect is almost certainly due to the fact that the samples of quartz, Sea Island, and Podunk soils were run in the same desiccator. The latter two soils holding less water, reached the dry state first, and when they no longer gave up water to the surrounding atmosphere the rate of evaporation for Sea Island cotton soil increased, thus producing the displacement in the curve. This observation emphasizes the necessity of closely regulating the conditions for evaporation studies.

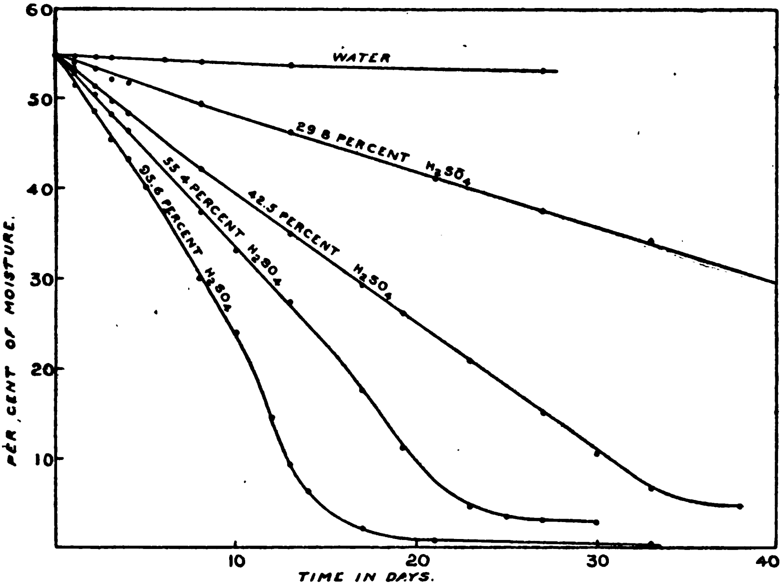

FIG. 3.—Curves for Sea Island cotton soil, showing effect of humidity upon rate of evaporation.

The influence of the presence of organic matter in a soil is shown by a comparison of the evaporation curves for quartz, Podunk, and Sea Island soils over concentrated sulphuric acid. The presence of organic matter in Sea Island soil increases its water-holding power some 25 per cent above that of quartz or Podunk soil, but it does not decrease the rate of evaporation, for the Sea Island curves are very nearly parallel to those for Podunk fine sandy loam and for quartz.

The foregoing study is important in that it gives a valid basis for applying the experimental results determined for one humidity condition to any other humidity condition. Because of the high rate of evaporation and slow change in vapor pressure of the acid, it is preferable to use concentrated sulphuric acid in evaporation studies. Results thus obtained may be confidently used for general application.

The relation of the length of time required for a soil to dry out to the atmospheric humidity is of great agricultural interest. Equal changes in humidity correspond to very unequal periods required for a soil to dry. Thus, for quartz, 60 days would be required to reach an air-dry condition with an atmospheric humidity of 75 per cent: 26 days with 50 per cent humidity; 16 days with 25 per cent humidity, and the proportionately long period of 10 days with 1 per cent humidity.

The rate of evaporation curves show, too, that wet soil in an atmosphere saturated with water vapor slowly loses weight. This loss may be due to several disturbing influences.

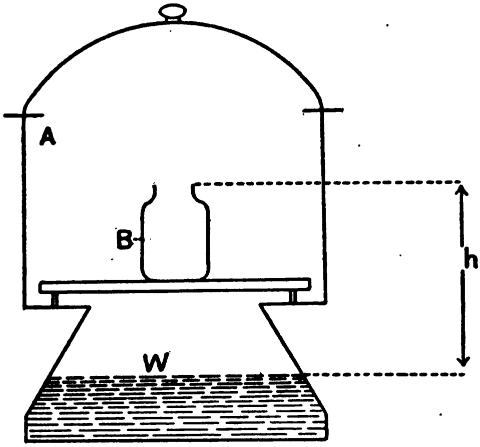

FIG. 4.—Drawing of desiccator containing soil sample.

There is a slight difference in the vapor pressure of the water in the bottle B and the water W, caused by the weight of a column of vapor of height *h* (see fig. 4). $P_b - P_w = hd$, where P_b and P_w are the vapor pressures at the level in the bottle and at the lower water surface W, respectively, and *d* is the density of the vapor. Although this value is very small, it is theoretically of interest and might enter into calculation when the time factor is large.

Small changes in temperature would cause loss of water from the weighing bottle containing moist soil. If the temperature rises a little this will first affect the desiccator near the outside wall, at A, figure 4. The increase in temperature momentarily reduces the relative humidity, thus disturbing the equilibrium. In order to restore equilibrium water vapor moves from the interior of the desiccator near B toward A. This produces at the same time evaporation of the water in B and of the water at W in the bottom of the desiccator. If a slight drop in the temperature within the thermostat now takes place cooling will first occur at A, followed by supersaturation and finally by condensation of moisture at A until equilibrium is again established. This cooling, however, will not produce a condensation upon the surface of the soil equal in amount to the loss by evaporation due to rise in temperature. Thus a slow loss of water from soil will result.

The thermostat was heated by an incandescent electric lamp, consequently a black soil might absorb sufficient radiant energy to maintain its temperature slightly above that of the surrounding medium. The vapor pressure of the warmer soil moisture would be higher, and a distillation of water from B to W would result.

Opening the desiccator for estimation of the moisture in soil would reduce the humidity and cause evaporation from the soil when replaced after weighing.

ABSORPTION STUDIES.

Experimental data.

The absorption of moisture by air-dry soils in an atmosphere saturated with water vapor is shown by the data given in Tables II, III, and IV for quartz, Podunk fine sandy loam, and Sea Island cotton soils at 25° C. As stated above, these experiments were carried out with weighing bottles placed in a desiccator. A parallel set of experiments using shallow aluminum dishes showed that the dishes do not give so great gain in moisture as is obtained when weighing bottles are used. The three soils used here were in air-dry condition at the start; their moisture content in percentage is given in Tables II, III, and IV.

A set of absorption experiments was carried out, using other soils and soil separates which had been heated to constant weight at 110° C. and then placed in a saturated atmosphere at 28° C. This set was not subjected to such accurate temperature control as those given above, still the curves obtained by plotting gain in moisture against time of absorption are very regular and the data fairly characteristic. The data are given in Table V.

TABLE V.—*Water vapor absorbed by soils from a saturated atmosphere at 28° C.*

Period.	Galveston clay.	Hagerstown loam.	Marshall silt loam.	Norfolk sand.	Quartz.
Days.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	4.699	1.717	1.823	0.169	0.144
2	5.896	2.047	2.220	.220	.203
3	6.504	2.363	2.455	.240	.245
14	8.928	3.152	2.990	.322	.417
19	9.685	3.317	3.160	.334	.420
23	9.779	3.625	3.383	.354	.502
31	10.228	3.974	3.603	.390	.574
34	10.277	4.014	3.611	....	....
37	10.373	4.107	3.713	.416	.625
49	10.841	4.553	4.005	.440	.752
AREA PER GRAM.					
	Sq. cm.	*Sq. cm.*	*Sq. cm.*	*Sq. cm.*	*Sq. cm.*
	3,280	2,270	2,320	300	1,260

Discussion.

At the bottom of Table V is given the area of each soil in square centimeters per gram as calculated from its mechanical analysis. This affords a rough comparison of soil texture with absorptive power, and shows that in a broad way the absorptive power is greater for soils of fine texture, as would be expected. Galveston clay absorbs three times the mass of water vapor that Marshall silt loam takes up, while the calculated area of the clay per gram is not three times greater, but less than a third greater, than for the silt loam.

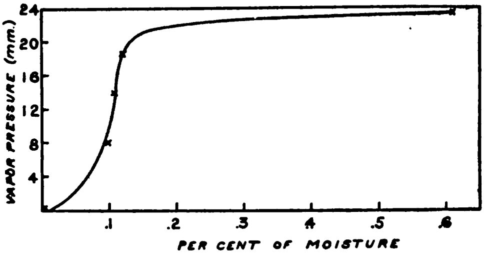

FIG. 5.—Curve showing variation of moisture in quartz flour with increase in atmospheric humidity.

DEPENDENCE OF MOISTURE CONTENT UPON HUMIDITY.

Table VI contains a summary of the equilibrium points already given in Tables II, III, and IV—that is, the percentage of moisture retained by each soil over each strength of sulphuric acid, a quantity which is practically the same as the percentage absorbed by the air-dry soil from air saturated with moisture over the different concentrations of sulphuric acid used. Of course, during the evaporation from the moist soil the sulphuric acid in each desiccator became diluted.

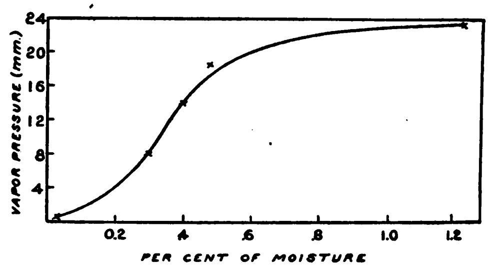

FIG. 6.—Curve showing variation of moisture in Podunk soil with increase in atmospheric humiditv.

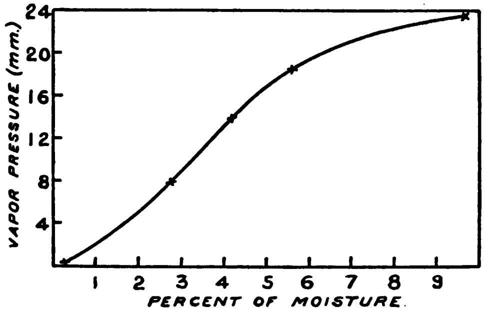

FIG. 7.—Curve showing variation of moisture in Sea Island cotton soil with increase in atmospheric humidity.

In Table VI is given the initial and final strength of each portion of acid and the corresponding partial pressures of water vapor over this acid. Opposite these acid percentages are found the moisture contents of each soil, quartz, Podunk, and Sea Island.

In figures 5, 6, and 7 curves are plotted from the data given in Table VI, showing the variation in moisture content of each soil with increasing atmospheric humidity. Ordinates are in partial pressures of water vapor expressed in millimeters of mercury; abscissas percentage of water in the soil.

TABLE VI.—*Variation of moisture content of soil with humidity under equilibrium conditions at 25° C.*

Strength of sulphuric acid.				Quartz.		Podunk.		Sea Island.	
Initial.		Final.		Drying out.	Absorbing moisture.	Drying out.	Absorbing moisture.	Drying out.	Absorbing moisture.
Per cent	*Mm.*	*Per cent*	*Mm.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
94.00	0.01	88.3	0.09	0.07	0.07	0.04	0.02	0.34	0.47
55.40	6.00	51.2	8.00	.09	.10	.30	.30	2.80	2.80
42.55	12.00	39.0	14.00	.11	.11	.43	.40	4.20	4.10
29.84	17.90	27.1	18.30	.12	.12	.51	.48	6.08	5.60
Water.	23.50	Water.	23.50	....	.61	....	1.24	....	9.70

The point on each of these curves figures 5, 6, and 7 corresponding to 23.5 mm., the partial pressure of water vapor at 25° C., may be high on account of the "dew point" effect produced by even slight temperature changes, as suggested in the previous discussion.

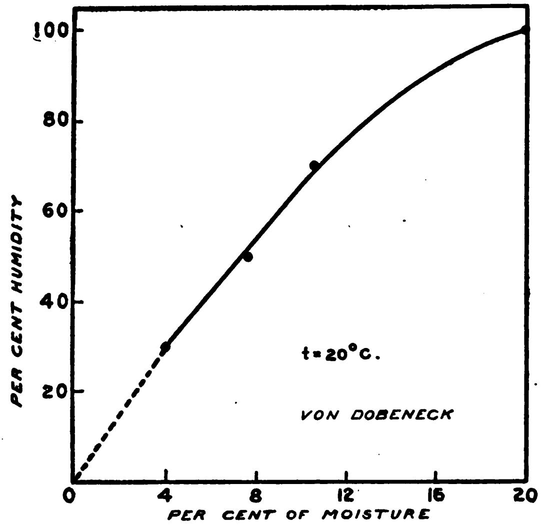

FIG. 8.—Curve showing variation of moisture in humus with increase in atmospheric humidity.

Because of the wide range through which the moisture content varies, the curve for Sea Island cotton soil in figure 7 is probably the most correctly determined. Owing to its low percentage of absorbed water, errors caused by slight temperature changes are greater relatively for quartz, and its curve in figure 5 is less accurate. These curves in figures 5, 6, and 7 resemble those given by van Bemmelen[a] for the absorption of water vapor by silicic acid at various partial pressures, save that for these soils no certain hysteresis effect is shown. However, we are here dealing with an adsorption effect rather than with imbibition, especially in the case of quartz flour; whereas van Bemmelen's hysteresis effect occurs with the colloidal silicic acid and is due mainly to imbibition; indeed, he gives data showing that the fineness of the silicic acid particles has no marked effect upon the mass of water vapor absorbed.

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[a] Zeit. anorg. Chem., 13, 233 (1896-97).

For comparison with this data, von Dobeneck's work upon the absorption of water vapor by humus in atmospheres of different humidity is given in Table VII. The equilibrium points are plotted in figure 8 and give a curve similar in form to that in figure 6 for the Podunk soil.

TABLE VII.—*Change in moisture content of humus submitted to atmospheres of different degrees of humidity at 20° C., according to von Dobeneck.*

Humidity 30 per cent.		Humidity 50 per cent.		Humidity 70 per cent.		Humidity 90 per cent.		Humidity 100 per cent.	
Period.	Moisture absorbed.	Period.	Moisture absorbed.	Period.	Moisture absorbed.	Period.	Moisture absorbed.	Period.	Moisture absorbed.
Days.	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*	*Days.*	*Per cent.*
1	1.68	1	[a] 4.91	1	[a] 8.03	1	[a] 10.85	1	[a] 16.11
2	2.96	2	5.77	2	8.47	2	11.28	2	16.49
3	3.47	3	6.41	3	8.74	3	11.65	3	16.75
4	3.62	4	6.96	4	9.00	4	12.06	4	16.93
5	3.68	5	7.36	5	9.31	5	12.48	5	17.09
6	3.73	6	7.60	6	9.51	6	12.96	6	17.29
7	3.80	7	7.63	7	9.70	7	13.44	7	17.50
8	3.94	8	7.68	8	9.77	8	13.94	8	17.71
9	3.99	9	7.74	9	9.94	9	14.28	9	17.83
10	4.01	10	7.75	10	10.16	10	14.56	10	17.85
11	4.03	11	7.76	11	10.27	11	14.95	11	17.89
12	4.05	....	....	12	10.32	12	15.24	12	17.90
....	....	....	....	13	10.47	13	15.27	13	17.96
....	....	....	....	14	10.42	14	15.36	14	18.02
....	....	....	....	15	10.48	15	15.44	....	....
....	....	....	....	16	10.54	16	15.49	....	....
....	....	....	....	17	10.57	17	15.55	....	....
....	....	....	....	18	10.58	18	15.59	....	....
....	....	....	....	19	10.59	19	15.63	....	....
....	....	....	....	20	10.58	20	15.67	....	....

[a] The sample of humus after being saturated in an atmosphere of a given degree of humidity was placed in an atmosphere of higher humidity and allowed to reach equilibrium. This process was continued up to an atmosphere of 100 per cent humidity.

ABSORPTION OF OTHER VAPORS.

In Table VIII is given the percentage of toluene ($C_6H_5.CH_3$) vapor absorbed by Galveston, Hagerstown, Marshall, and Norfolk soils and quartz from a saturated atmosphere at 28° C. Similarly, Table IX contains the percentage of ether taken up by the soils at 27° C. from an atmosphere consisting entirely of ether vapor. Comparing these results with those given in Table V it is seen that Galveston clay has the same relative absorptive power for toluene and for water, although the mass of water vapor retained is almost exactly twice that of the toluene. The Hagerstown, Marshall, and Norfolk soils absorb toluene vapor to the extent of slightly less than half the mass of water vapor each soil can take up. Galveston clay absorbs about one-half more ether than water by weight, while the reverse is true of Norfolk sand, and the other two soils take up about the same quantity of ether as of water. Table X gives the absorption of water, ether, and toluene vapors at 28° C. by a soil separate fraction obtained in the mechanical analysis of soils[a] whose grains varied from 0.1 to 0.05 mm. in diameter. Here the absorption of ether vapor is slightly higher than that of water, and the toluene considerably lower. Still the quantities of all three vapors absorbed are of the same order of magnitude.

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[a] See Bul. No. 24, Bureau of Soils, U. S. Dept. Agr. (1904).

TABLE VIII.—*Toluene vapor absorbed by soils from a saturated atmosphere at 28° C.*

Period.	Galveston clay.	Hagerstown loam.	Marshall silt loam.	Norfolk sand.	Quartz.
Hours.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
18.00	2.400	0.860	0.810	0.078	0.112
25.25	2.697	....	.853	.083	....
67.00	3.797	1.367	1.297	.117	.192
139.00	4.467	1.736	1.529	.138	.272
187.00	4.791	1.851	1.615	.167	.285
477.00	5.318	1.866	1.759	.185	.285

TABLE IX.—*Ether vapor absorbed by soils, at 27° C., 575 mm. pressure.*

Period.	Galveston clay.	Hagerstown loam.	Marshall silt loam.	Norfolk sand.
Days.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
0.75	4.320	2.625	2.320	0.421
11.75	4.840	3.580	3.070	.459
16.75	5.015	3.82	3.310	.470
28.00	5.760	3.995	3.605	.618
31.00	5.870	4.371	3.895	.618

TABLE X.—*Absorption of water, ether, and toluene vapors by a soil separate (0.1–0.05 mm.), at 28° C.*

Period.	Toluene.	Ether.	Water.
Hours.	*Per cent.*	*Per cent.*	*Per cent.*
17.75	0.264	0.481	0.367
25.50	....	.515	.418
35.00	.343	....	....
42.75	....	.699	.539
106.75	.396	....	....
114.50	....	.763	.609
154.25	.405	....	....
162.00	....	....	.624
352.00	....	....	.718

ABSORPTION OF GASES.

Absorption of air.

Reichardt and Blumtritt[a] recovered the gas absorbed by various soils and soil constituents from the atmosphere and analyzed it to ascertain what proportion of each atmospheric gas was held fixed in the soil. Their results are given in Table XI, and show that nitrogen is absorbed to a much greater extent than oxygen, and that each gas is retained to a different degree by different substances, a clear indication of the selective power which solids and gases mutually exert in absorption.

Dewar[b] has shown that all the inert gases—argon, helium, neon, krypton—can be condensed in charcoal as effectively as ordinary gases at suitable pressure and temperature.

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[a] Jour. prakt. Chem., **98**, 476 (1866).

[b] Proc. Roy. Soc., **74**, 130 (1904).

TABLE XI.—*Absorption of atmospheric gases by various substances, according to Reichardt and Blumtritt.*

Substance.	Gas per 100 grams.	Ratio, by volume.		
		Nitrogen.	Oxygen.	CO_2.
	C. c.	*Per cent.*	*Per cent.*	*Per cent.*
Charcoal, air dry	164	100	0	0
Peat	162	44	5	51
Garden soil	14	65	2	33
$Fe(OH)_3$, air dry	375	26	4	70
Fe_2O_3, ignited	39	83	13	4
$Al(OH)_3$, air dry	69	41	0	59
Alumina, dried at 100° C	11	83	17	0
Clay	33	65	21	14
Clay, moistened	29	60	6	34
River silt	40	68	0	32
Magnesium carbonate	729	64	7	29
Gypsum, pulverized	17	81	19	0

Absorption of oxygen.

In addition to the experiments of de Saussure, Smith, Stenhouse, and Reichardt and Blumtritt, several series of investigations have been carried out upon the absorption of oxygen gas. Joulin,[a] working with ignited charcoal, found that oxygen was so quickly absorbed that measurements on the velocity of absorption were not possible with the means at his command. Baker[b] has shown that a temperature of 450° C. is required to recover the gas from charcoal which has absorbed dry oxygen, and that the gas thus obtained is mainly carbon monoxide, only a little carbon dioxide being formed. Dewar,[c] on the other hand, by using a low-temperature bath of liquid air has succeeded in absorbing in charcoal more oxygen than nitrogen from the atmosphere, and upon warming the charcoal to ordinary room temperature again a large part of this oxygen is liberated, along with nitrogen, thus affording a ready means of obtaining oxygen from air by simply repeating the absorption and liberation process till the oxygen has the desired degree of purity. Richards and Rogers,[d] too, have shown that zinc oxide derived from the nitrate, even when heated to very high temperatures, retains nitrogen and oxygen. Morse and Arbuckle[e] confirmed these results, but found no evidence supporting Richards and Rogers's conclusion that the absorbed oxygen escapes more readily than the nitrogen. The zinc oxide was heated by Morse and Arbuckle to a temperature sufficient to melt cast steel and still retained per gram of oxide some 0.3 c. c. of gas whose composition varied—the nitrogen between 64.32 and 68.18 per cent, and the oxygen correspondingly, while the total volume of occluded gas was very nearly constant for eight different experiments.

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[a] Compt. rend., **90**, 741 (1880).

[b] Jour. Chem. Soc., **51**, 249 (1887).

[c] Chem. News, **94**, 174 (1906).

[d] Proc. Am. Acad., **28**, 200 (1893).

[e] Am. Chem. Jour., **20**, 200 (1898).

Absorption of nitrogen.

The absorption of nitrogen by soils has been studied mostly in connection with the absorption of atmospheric gases. From the work of Reichardt and Blumtritt, cited above, it appears that in general nitrogen is absorbed by soils in greater quantity than oxygen. This fact is especially worthy of note, since the absorption of oxygen and nitrogen from air by water gives a higher ratio of oxygen to nitrogen in the solution than the 1:4 relation which exists in air. The explanation immediately suggested is that oxygen is converted to carbon dioxide in the soil by action of the decomposing organic matter. But the similar high absorptive power of aluminum hydroxide, ferric hydroxide, and magnesium carbonate for nitrogen indicates that this is a real phenomenon, since these substances have no way of masking their true absorptive power for oxygen by converting it chemically to carbon dioxide, as a soil does, or to other oxides. Gypsum, too, preserves the ratio 81:19 of nitrogen to oxygen when it absorbs these gases from the air.

Absorption of carbon dioxide.

The determination of the actual quantity of carbon dioxide taken up by a soil from air is difficult, since the absorbed oxygen acts upon the organic matter in the soil to yield carbon dioxide, and the decaying organic matter itself contains carbon and oxygen which adds still more carbon dioxide to the soil atmosphere. The absorption of carbon dioxide from an atmosphere containing this gas alone can be estimated by the reduction of vapor pressure, by a density determination of the gas, or by determining chemically its weight in a given volume of the gas before and after contact with the soil.

Reichardt and Blumtritt determined the per cent by volume of carbon dioxide absorbed by soils and soil constituents. They showed that it is probable that the oxygen of the absorbed air is converted to CO_2 in the peat; of 162 c. c. gas absorbed from air, 44 per cent appears as nitrogen, 5 per cent as oxygen and 51 per cent as carbon dioxide. A similar relation is seen for the garden soil, moistened clay, and river silt. The ignited ferric oxide and aluminum oxide both show higher absorption of oxygen than the hydrated oxides, and lower absorption of carbon dioxide. This indicates that the absorption of carbon dioxide is dependent to a considerable extent upon the presence of water in the absorbing material, further evidence being afforded by the higher absorption of carbon dioxide by the moist clay.

Scheermesser[a] has stated that the amount of carbon dioxide absorbed by a dry soil is proportional to the amount of ferric oxide present, which would appear to be a generalization based on too few observations. Von Dobeneck[a] gives the carbon dioxide absorbed by soil constituents as follows:

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[a] Inaug.-Diss. Jena, 1871; ref. Chem. Centr., 1871, 462.

TABLE XII.—*Absorption of carbon dioxide by soil constituents according to von Dobeneck.*

Soil constituents, 100 grams.	CO_2 absorbed at—			
	0° C.	10° C.	20° C.	30° C.
	Grams.	*Grams.*	*Grams.*	*Grams.*
Quartz	0.023	0.021	0.023	0.022
Kaolin	.329	.298	.261	.215
Humus	2.501	2.125	1.773	1.479
$Fe(OH)_3$	6.975	5.702	5.054	4.274
$CaCO_3$	.028	.053	.034	.019

Kayser[b] attempted to express in absolute units the dependence of the absorption by glass fiber upon temperature and pressure. His aim was to measure the quantity of gas condensed by a known surface under definite temperature and pressure (and therefore with known concentration of the vapor phase) and to utilize this relation to estimate the surface of fine powders from the quantity of gas they absorb. But he was forced to abandon this, since adsorption is not dependent solely upon extent of surface, temperature, and pressure. He found (1) that glass fiber dried for a long time at high temperature adsorbs carbon dioxide, a few hours being required for saturation; (2) the adsorption increases with the pressure, and (3) decreases as the temperature increases.

A little later Bunsen,[c] using similar materials (glass fiber and carbon dioxide), obtained results at variance with those of Kayser, as follows: (1) Glass is not saturated with carbon dioxide in days or months, but only after several years have elapsed. Thus 1 sq. cm. of glass adsorbed of carbon dioxide at the end of the first year, 3.15 c. c.; second year, 1.10 c. c. more; third year, 0.88 c. c. more. (2) Sudden pressure and temperature changes never produced a noticeable evaporation of adsorbed carbon dioxide. (3) Sudden change of pressure within one atmosphere showed no effect upon the steady course of adsorption. (4) Within a temperature interval of 0.8° to 23° C., rise in temperature favored adsorption and conversely.

Bunsen[d] then showed that the difference between his results and those of Kayser lay in the method used to dry the glass fiber. At ordinary temperature glass may retain even in very dry air (over P_2O_5) a layer of water as thick at 10.55×10^{-6} mm., and at 107° C. up to $7.03 \times 10{-}^{6}$ mm.

Thus it is easy to understand why pressure changes within one atmosphere show little or no effect upon the rate of formation of these thin films where the pressure amounts to hundreds of atmospheres. Likewise the solution of gases in these thin films under high pressure appears reasonable, as well as the long period of time necessary for the establishment of equilibrium.

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[a] Forsch. Geb. Agr.-Phys., **15,** 201 (1892).

[b] Ann. Phys. Chem., **14,** 450 (1881).

[c] Ann. Phys. Chem., **20,** 545 (1883); **22,** 145 (1884).

[d] Ann. Phys. Chem., **24,** 321 (1885).

Mülfarth[a] has investigated the adsorption of gases by glass powders, with the following results: (1) Perfectly dry glass powder adsorbs a considerable mass of carbon dioxide. This is contrary to the experimental results of Krause.[b] (2) Glass powder dried at 420° C. and rendered free from gas shows an adsorption of carbon dioxide as great as glass dried at 500°. (3) The adsorption of the CO_2 by completely dried glass powder is normal; that is to say, it increases with increasing pressure and decreases with increasing temperature. (4) The adsorption of carbon dioxide by dried glass powder is completed in a short time—from one to two hours. (5) The presence of moisture renders the adsorption of CO_2 slower; nevertheless, in a few days it proceeds to completion, and the mass adsorbed is not greatly different from that taken up by dried glass powder at the same pressure and temperature. Consequently, the main influence of dampness appears to consist in rendering the process of adsorption slower. (6) The quantity of carbon dioxide adsorbed is not nearly so great as Bunsen found in his research using glass fiber. (7) The adsorption of sulphur dioxide by dried glass powder proceeds exactly like that of carbon dioxide, is completed in two hours, increases with increasing pressure, and decreases with increasing temperature. (8) At zero degress the following gases are adsorbed by glass powder and in the following order: Ammonia, sulphur dioxide, carbon dioxide, nitrous oxide (N_2O), acetylene, in descending series. The gases, sulphur dioxide and ammonia, which are most easily condensed to liquid, are the most strongly adsorbed. Nitrous oxide and carbon dioxide, which stand very near to each other in respect to the ease of their condensation at low pressures, are almost equally well adsorbed, but carbon dioxide a little more strongly. (9) Henry's law holds fairly well also for the adsorption of gas on glass powder.

Absorption of ammonia.

Ammon[c] found that ammonia is absorbed by soil constituents as follows: Humus at 20° C., 11.5 per cent of its dry weight; ferric hydroxide, 4.7; quartz powder, 0.295; calcium carbonate, 0.23; kaolin, 0.42. When pure ammonia gas is absorbed, small quantities of nitric acid are formed, relatively more in ferric hydroxide than in the other soil constituents. The absorption of ammonia in general decreases with increase in temperature, but near zero, Centigrade, the maximum quantity of gas is taken up, less being absorbed at lower as well as at higher temperatures. In view of the more recent work by Dewar[d] and others on the absorption of gases at low temperatures the actual existence of such a maximum as Ammon found is open to question.

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[a] Ann. Phys. (4), **3**, 328 (1900).

[b] Ann. Phys. Chem., **36**, 923 (1889).

[c] Forsch. Agr.-Phys., **2**, 34 (1879).

[d] Chem. News, **94**, 174 (1906).

Von Dobeneck[a] has confirmed Ammon's conclusion that the absorption of ammonia is less the higher the temperature when working above zero, Centigrade. Von Dobeneck's quantitative measurements on the absorption of ammonia are in general of the same order of magnitude as those given by Ammon, and in addition von Dobeneck has shown that mixtures of soil constituents absorb ammonia and other gases additively, each material exerting its absorption effect independently of the others. He showed, too, that where a moist powder absorbs ammonia, the quantity of gas retained is very considerably in excess of what the water can dissolve when separate from the powder. Thus, 100 grams water dissolved 43.9 grams of ammonia, but when this same mass of water was held by 854 grams of kaolin, 56.5 grams of ammonia were absorbed, an increase of 28.6 per cent; with 472 grams kaolin and 100 grams water, 55.7 grams ammonia were absorbed. Similarly the following powdered solids, each wet with 100 grams water absorbed ammonia: 445 grams calcium carbonate, 54.6 grams; 435 grams quartz, 53.1 grams; 329 grams kaolin, 54.0 grams; 200 grams ferric hydroxide, 47.2 grams; 202 grams humus, 78.5 grams; 186 grams kaolin, 51.9 grams.

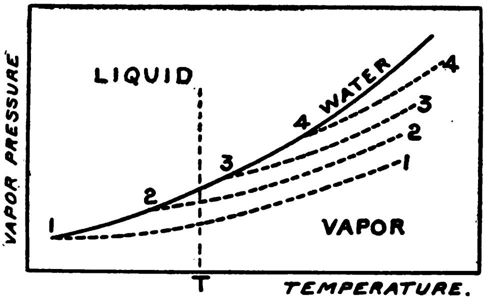

Fig. 9.—Curves showing vapor pressure of water, and of moist soils at various temperatures for case I, assuming that absorption increases with rise in temperature.

Schlösing[b] found that soils, whether acid or alkaline, dry or wet, absorbed ammonia from the atmosphere in appreciable amount. Calcium carbonate in the soil increases the absorption capacity of the soil for ammonia. Absorption is in a high degree dependent upon a continual renewal of air at the surface of the soil, consequently, it makes a difference whether the surface be bare or covered with vegetation, since the plants tend to prevent circulation of the air in a layer near the surface.

Pfeiffer[c] showed that equal changes in pressure produce about equal changes in the quantity of gas absorbed by different sorts of carbon. He found that the absorption of ammonia by charcoal decreased about one-half on heating from 0° to 70° C.

Absorption of hydrogen.

The absorption of hydrogen is of minor importance from the standpoint of soil chemistry. Joulin[d] showed that ignited charcoal absorbs hydrogen so rapidly as to render difficult a measurement of the velocity, and recently Travers[a] has studied the absorption of hydrogen by cocoanut charcoal at different temperatures. The numerous investigations on the absorption of hydrogen by metals need only be mentioned in this connection.[b]

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[a] Forsch. Agr.-Phys., **15**, 201 (1892). [b] Compt. rend., **110**, 429, 99 (1890).

[c] Über die Verdichtung von Gasen durch feste Körper; Inaug. Diss. Erlangen (1882).

[d] Compt. rend., **90**, 741 (1880).

EFFECT OF TEMPERATURE UPON ABSORPTION.

THEORETICAL CONSIDERATIONS.

Assuming for the particular substance, water, that the quantity of moisture absorbed by a soil from a saturated atmosphere varies with the temperature, there are two possible cases:

(1) The amount of water absorbed increases with the rise in temperature. For this case the vapor-pressure-temperature curves for the soils will cut the vapor-pressure-temperature curve for water, as shown in figure 9; this has apparently been realized experimentally by Hilgard.[c]

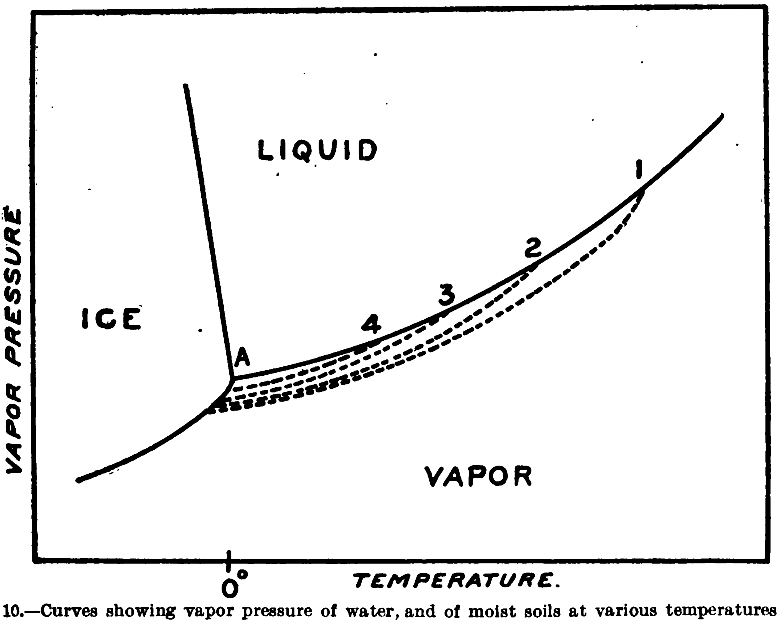

FIG. 10.—Curves showing vapor pressure of water, and of moist soils at various temperatures for case II, assuming that absorption decreases with rise in temperature.

(2) The amount of water absorbed from a saturated atmosphere decreases with rise in temperature. This case is illustrated by figure 10. Here the lower limit of the vapor-pressure curves for soils is the vapor-pressure-temperature curve for ice, and the maximum quantity of water absorbed at any temperature whatever is the mass of water which can remain adsorbed by the soil, in equilibrium with

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[a] Proc. Roy. Soc. London, 78, Ser. A, 9–22 (1906).

[b] See Fischer, Ann. Phys. (4), 20, 503 (1906).

[c] "Soils," pp. 196, 198 (1906).

the complete system—ice, "liquid water," water vapor, which exists at the triple point A. The dotted curves in figure 10 show the vapor-pressure-temperature curves for soils. The quantity of moisture in the soil remains constant along the dotted curve, which is limited in extent; above, it meets the vapor-pressure curve of liquid water; below, it cuts the vapor-pressure curve for ice. Here the absorbed water would begin to freeze at a lower temperature than free water; and when we remember the enormous stress under which water exists when in adsorbed condition, this conclusion is not surprising.

EXPERIMENTAL DATA AND DISCUSSION.

Four series of preliminary experiments were carried out. In the first three series 10-gram samples of dry quartz flour, Podunk fine sandy loam, and Sea Island cotton soil were brought to equilibrium with water vapor in desiccators at various temperatures in the thermostat. The general trend of these results serves very well to show that the mass of water vapor absorbed decreases with the temperature. And by comparison of this series for Sea Island cotton with a later series for the same soil under rigid conditions, using stoppered weighing bottles to avoid loss of moisture on the balance, the exact experimental error is seen at each point.

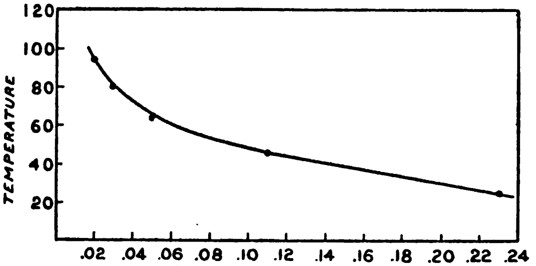

FIG. 11.—Curve showing decrease in absorption of water vapor by quartz flour with rise in temperature.

The results for quartz flour given in Table XIII and plotted in figure 11 show a decrease of 91 per cent in the water absorbed for an increase of 74° C.

TABLE XIII.—*Decrease of absorption with temperature rise for quartz flour*[a] *in open dish over water.*

Temperature.	Water held by soil.
°*C.*	*Per cent.*
23	0.23
43	.11
62	.05
80	.03
97	.02

[a] The same sample was used throughout.

TABLE XIV.—*Decrease of absorption with temperature rise for Podunk soil in open dish over water.*

Temperature.	Water held by soil.
°*C.*	*Per cent.*
25	0.81
43	.35
62	.16
80	.11

TABLE XV.—*Decrease of absorption with temperature rise for Sea Island cotton soil in open dish over water.*

Temperature.	Water held by soil.
°*C.*	*Per cent.*
25	8.4
62	4.84
80	3.84

TABLE XVI.—*Decrease of absorption with temperature rise for Sea Island cotton soil in weighing bottles over water.*

Temperature.	Water held by soil.
°*C.*	*Per cent.*
25	9.7
100	5.5 5.4

Podunk fine sandy loam confirms the general trend shown by quartz, as seen in Table XIV and figure 12. The soil absorbs over 50 per cent less water vapor at 43° than at 25°, and a rise in temperature of only 55°, from 25° to 80°, reduces the moisture content at equilibrium by 86 per cent. Sea Island soil in open dishes over water shows in Table XV a decrease in absorption of 42 per cent for a rise of 32°, and of 54.2 per cent for 55°.

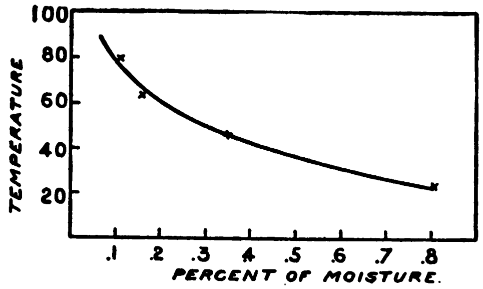

FIG. 12.—Curve showing decrease in absorption of water vapor by Podunk soil with rise in temperature.

A fourth series for Sea Island cotton soil is given in Table XVI. The quantity of water absorbed at 25° over water in a desiccator was determined, using a 20-gram sample in a weighing bottle which could be closed during the weighing to avoid evaporation. The data for this point are taken from the lower half of Table IV and were obtained under accurately controlled temperature conditions; the equilibrium conditions were established after a run of ninety-seven days.

The absorption at 100° C. was found by inclosing the weighing bottle with its 20-gram soil sample in a sealed tube over water. This tube was immersed in boiling water, as shown in figure 13, where T is the sealed tube; W, the weighing bottle; S, a copper support to hold the bottle out of the water; G, a safety guard of gauze surrounding the tube T and also serving as a support; C, a cork support for T and G; H, hooks holding the gauze G to the cork C; B$_1$, a beaker containing boiling water nearly to the level of the cork C; B$_2$, a tall beaker inverted over B$_1$ and serving as a condenser.

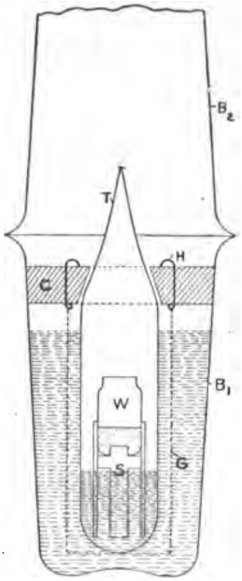

FIG. 13.—Diagram of apparatus used to determine absorption of water vapor by soil at the boiling point of water.

With this arrangement water need be added to B$_1$ only every two days. On account of the high temperature, absorption proceeded rapidly to completion; equilibrium was established within a week, as shown by the values given in Table XVI. After one week 5.5 per cent of moisture had been absorbed, and another week's run gave practically the same value, 5.4 per cent; so the system had come to equilibrium. The difficulty met with in the other experiments, Tables XIII, XIV, and XV, did not enter here, since a closed weighing bottle was used.

The data for the two points in Table XVI are shown in figure 14 as curve 1, and for comparison the data from Table XV are given on the same plot and to the same scale, with temperature as ordinate and percentage moisture in the soil as abscissa. It is evident that the determinations made in open dishes, curve 2, show less moisture than those made in weighing bottles, curve 1. At 80° C. this loss of absorbed moisture from an open evaporating dish during weighing amounts to nearly 40 per cent, at 25° C. this loss is 13 per cent, and for 100° C. extrapolation of curve 2 indicates a loss of some 48 per cent of the total. The curves in figs. 11,

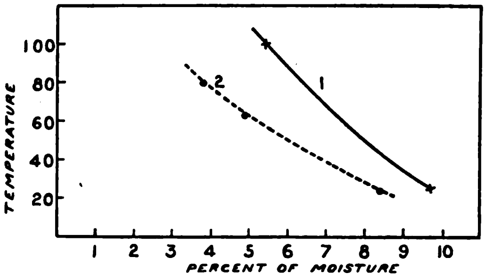

FIG. 14.—Curve showing decrease of absorption of water vapor by Sea Island cotton soil with rise of temperature.

12, and 14 show the same general trend, and together with the most accurately determined points in Table XVI and curve 1, figure 14, show a decrease of absorption as temperature rises in a manner not open to question. All of these curves bend upward steeply at higher temperatures, since the absorbed moisture is held more firmly the thinner the layer in which it is spread upon the soil grains.

Thus it is proved experimentally that absorption of water vapor by soils decreases very greatly with rise in temperature. A departure from equilibrium conditions, which indeed seldom obtain in the field, shows even greater decrease in the quantity of absorbed water as the temperature increases.

ABSORPTION CAPACITY.

It is of interest to see how the absorption data are related to the surface presented by the grains of the different soils used. For this purpose a general survey of the quantity of vapors absorbed by some of the soils studied in the foregoing sections is given in Table XVII.

Unfortunately the area of a soil as calculated from its mechanical analysis (Table XVIII) can give only an approximate result, probably much below the true value. Thus in Table XVII it is seen that Galveston clay absorbs three times the mass of water vapor that Marshall silt loam takes up, while the calculated area of the clay is not three times as great but less than a third greater than the silt loam. The results obtained with toluene were in general similar to those obtained with water. The ether vapor behaves differently, the clay taking in a smaller quantity than would be predicted from the water and toluene results.

Table XIX contains the calculated thickness of the layer of liquid absorbed upon the grains of each soil. The following assumptions were made in deriving these values: (1) That the film of absorbed vapor is uniform in thickness over all the soil grains; (2) density of water, 1; density of toluene, 0.89; density of ether, 0.73; as these densities are probably lower than the density of the surface film the value for the thickness of film is probably too high; (3) density of individual soil grains, 2.5; (4) that the soil grains are spheres; this assumption probably gives a value of the film thickness much too high; (5) that the fractions in the mechanical analyses are clean separations. In the last two fractions the diameters of the grains vary within relatively wide limits. The area of the soil grains is probably several times greater than the value given in Table XVII. For example, the quantity of water absorbed by Galveston clay is much greater than would be expected from its area when the absorption capacity of the other soils and their areas are considered. The clay and silt in the Galveston clay greatly increase its surface beyond that calculable from a mechanical analysis. It was on this account that the soil separate with grains varying only between 0.1 and 0.05 mm. in diameter was used in this series, so that a more accurately determined surface might be used for the determination of its absorption capacity.

TABLE XVII.—*Area of soil grains as related to absorption capacity for vapors.*

Soil.	Area per gram.	Water absorbed.		Ether absorbed.		Toluene absorbed.	
		Eight days.	Maximum.	Eight days.	Maximum.	Eight days.	Maximum.
	Sq. cm.	*Per ct.*	*Per cent.*	*Per ct.*	*Per cent.*	*Per ct.*	*Per cent.*
Galveston clay	3,280	8.00	12.00	4.80	6.00	4.79	....
Marshall silt loam	2,320	2.84	4.00	2.86	4.00	1.62	1.7
Hagerstown loam	2,270	2.90	4.50	3.30	4.50	1.85	....
Quartz flour	1,260	.35	.80	....	....	.29	.4
Soil separate (0.1-0.05)	320	.67	1.00	.77	.77	.41	....
Norfolk sand	300	.29	.45	.45	.62	.17	....

TABLE XVIII.—*Mechanical analyses.*

Soil.	Average diameter of grain.						
	2-1 mm.	1-0.5 mm.	0.5-0.25 mm.	0.25-0.1 mm.	0.1-0.05 mm.	0.05-0.005 mm.	0.005-0 mm.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Galveston clay	0.7	1.5	0.40	7.0	28.9	30.1	31.00
Hagerstown loam	.9	3.0	2.10	6.5	13.9	54.3	19.10
Marshall silt loam	1.3	2.8	1.70	4.3	12.9	56.9	19.50
Quartz flour	.0	.0	.05	.2	8.0	86.2	5.42
Norfolk sand	.2	6.3	22.20	63.7	4.1	1.0	1.80

TABLE XIX.—*Comparison of absorption capacity of soils for vapors.*

Soil.	Vapor.	Total quantity absorbed.	Quantity per sq. cm. × 10⁵.	Thickness of layer.	Energy = latent heat × grams absorbed.
		Grams.	*Grams.*	*Cm. × 10⁵.*	
Soil separate (0.1-0.05). 8 days absorption.	Water	0.6417	2.00	2.00	378.2
	Toluene	.4049	1.26	1.42	33.8
	Ether	.770	2.40	3.25	65.8
Galveston clay, maximum absorption	Water	12.00	3.66	3.66	7,080.0
	Toluene	6.00	1.83	2.06	501.0
	Ether	6.00	1.83	2.51	518.0
Marshall silt loam	Water	4.00	1.72	1.72	2,360.0
	Toluene	1.70	.73	.82	240.0
	Ether	4.00	1.72	2.35	345.0
Hagerstown loam	Water	4.50	1.98	1.98	2,655.0
	Toluene	1.85	.82	.92	155.0
	Ether	4.00	1.68	2.31	345.0
Norfolk sand	Water	.45	1.50	1.50	265.5
	Toluene	.25	.83	.94	20.9
	Ether	.62	2.06	2.83	53.5
Quartz flour	Water	.80	.64	.64	471.0
	Toluene	.40	.32	.36	334.0

TABLE XIX.—*Comparison of absorption capacity of soils for vapors*—Continued.

Soil.	Vapor.	Vapor pressure.	Temperature.	Surface tension.	Viscosity.	Density.
		Mm.	° *C.*	*C. G. S.*	*C. G. S.*	*C. G. S.*
Soil separate (0.1–0.05). 8 days absorption.	Water	28.1	28	73	0.01	1.00
	Toluene	33.5	28	28	.0056	.89
	Ether	575.0	28	17	.0024	.73
Galveston clay, maximum absorption.	Water	28.1				
	Toluene	33.5				
	Ether	575.0				
Marshall silt loam	Water	28.1				
	Toluene	33.5				
	Ether	575.0				
Hagerstown loam	Water	28.1				
	Toluene	33.5				
	Ether	575.0				
Norfolk sand	Water	28.1				
	Toluene	33.5				
	Ether	575.0				
Quartz flour	Water	28.1				
	Toluene	33.5				

This soil separate shows a film 2.0×10^{-5} cm. thick, as against a thickness of 3.66×10^{-5} cm. for Galveston clay and 1.5×10^{-5} for Norfolk sand, while Hagerstown loam and Marshall silt loam give values nearer that of the soil separate. Parks[a] gives a value for the thickness of a water film absorbed on glass wool, 1.34×10^{-5} cm., which agrees closely with these results.

In general, toluene gives a thinner film than water, while the ether layer is thicker than that of water for all soils save Galveston clay.

If we assume the average diameter of a clay particle as 0.0002 cm., and consider it to be a sphere, its volume is 4.19×10^{-12} c. c. If the water film be uniform in thickness over the surface of all the grains, 2.00×10^{-5} cm., as given for the soil separate, then the total volume of this clay particle with its absorbed water will be 7.25×10^{-12} c. c., and the volume of water alone 3.06×10^{-12} c. c., or 73 per cent of the volume of the clay particle holding it, and the radius of the particle is only ten times greater than the thickness of the water layer surrounding it. There is very little doubt that this hygroscopic water is in part held in the fine capillary spaces between the soil grains,[b] but we have no sharp experimental method of ascertaining what fraction of the water is thus retained.

A comparison of the quantities of water, toluene, and ether absorbed by the various soils, with their surface tensions, viscosities, vapor pressures, and latent heats of evaporation does not give a clue to the different absorption capacities found. It seems that each vapor has its own specific action which finds a counterpart in the selective absorption exercised by the soil. For any one vapor the absorption capacity of a soil is roughly proportional to the soil grain surface as calculated from the mechanical analysis.

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[a] Loc. cit.

[b] Katao, Über die Wasserbewegung in Boden, Bul. Col. Agr., Imp. Univ., Tokyo, Vol. 3, No. 1, 1897; Soyaka, Forsch. Agr. Phys. 8, 1 (1885); Whitney, Agricultural Science, Vol. 3, p. 199, 1889; Briggs, Bul. No. 10, U. S. Dept. of Agriculture, Division of Soils (1897).

Finally, we see from the above considerations that for any one vapor the amount of absorption is proportional to the calculated soil area exposed, and that the thickness of film on any given soil surface varies with the nature of the vapor, but the data at present available are not sufficient to show that the thickness of the film is dependent upon the nature of the soil type.

DISTRIBUTION.

Solids in general do not completely absorb gases or vapors, but rather the gas is divided between the atmosphere and the solid. The greater the quantity of gas or vapor in the atmosphere, the more of it is held fixed by the solid, until the solid becomes saturated and can retain no more of the gas. A number of attempts have been made to express this relation between the quantity absorbed by the solid and the concentration of gas in the atmosphere, as a fairly simple mathematical equation. The chemical composition of the solid and that of the gas of course determine in great measure the degree to which absorption takes place, and this factor is expressed by a constant which is different for each solid and gas studied. The effect of temperature upon absorption is likewise recognized in the formula by a constant whose value changes with the temperature.

De Saussure[a] has suggested the formula $V = 19.1 + 0.53\ P$, where V is the volume of gas adsorbed and P is the pressure in inches of mercury. This relation holds for carbon dioxide.

Ostwald[b] applies to gaseous adsorption the equation, $\frac{x}{m} = \alpha C^{\frac{1}{p}}$, which was developed for adsorption from solution, where x is the mass of gas adsorbed; m the mass of adsorbent solid; C the concentration of the vapor phase; α is a constant; and $\frac{1}{p}$ is an exponent. Freundlich holds that adsorption from solution and from vapor by solids follow the same law, and Ostwald's exponent, $\frac{1}{p}$ equals $1 - \frac{1}{n}$, where $\frac{1}{n}$ is the exponent in the equation,[c] $\lambda = \alpha \left(\frac{a}{v}\right)^{-\frac{1}{n}}$, proposed by himself.

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[a] Loc. cit.

[b] Lehrbuch der Allgemeine Chemie, II (2 Aufl.) 232.

[c] $\lambda = \alpha \left(\frac{a}{v}\right)^{-\frac{1}{n}}$ is simply an empirical relation, and is not derived analytically from the other equation, $\lambda = -\frac{v}{m} \ln \left(\frac{a}{a-x}\right)$ given by Freundlich. λ and α are constants; a is total mass of gas in the system, and v is the volume of space available for the gas.

Thus Freundlich found working with liquid solutions, values for $\frac{1}{n}$, which range from 0.86 to 0.485, giving to $\frac{1}{p}\left(=1-\frac{1}{n}\right)$ values from 0.14 to 0.515. But the $\frac{1}{p}$ given by Ostwald on the basis of Chappuis,[a] Joulin,[b] and Kayser's[c] results, for CO_2 adsorbed by various kinds of charcoal, is higher, varying from 0.50 to 0.75. Further, Chappuis's curve for $\log\frac{x}{m}$ against C is very concave for carbon dioxide, whereas if the exponential formula $\frac{x}{m}=\alpha C^{\frac{1}{p}}$ applies, this curve should be a straight line. So this formula of Ostwald's holds only indifferently well as far as this gas is concerned.

Recently Travers[d] has determined the distribution of hydrogen and of carbon dioxide between cocoanut charcoal and the vapor at 100°, 60°, 35°, 0° and $-78°$, and for hydrogen at $-190°$ C. He suggests the formula, $\sqrt[n]{\frac{P}{x}}=$ a constant, where P is the gas pressure and x the concentration of the gas, in the solid phase for each temperature. The value of n increases when the temperature falls. For CO_2 at 0°, $n=3$; at 100°, $n=2$; at higher temperatures n would probably equal 1 and then the distribution law would hold exactly—i. e., become linear—but it is possible, too, that n might fall below 1. Hydrogen at $-190°$ behaves exactly like CO_2 at 0°; that is, $n=3$. Travers attributes the departure of the distribution law from a linear form at low temperatures to the influence of diffusion into the solid phase. On the contrary, Trouton[e] has assumed the formation of a liquid phase upon the surface of the solid to explain his curves representing the absorption of water vapor by cotton.

It is seen that no one mathematical expression yet proposed describes the present data for the adsorption of gases by solids. The specific attractions of solid and gas, the diffusion of gas into solid, the condensation of gas to liquid, and the consequent clogging of capillary channels where the forms and arrangement of these minute spaces enter to determine the vapor pressure of the liquid there enmeshed, all these factors complicate the observed relation of mass of gas adsorbed to mass of gas left in the vapor phase.

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[a] Ann. Phys. Chem., **12**, 161 (1881).

[b] Ann. Chim. Phys. (5), **22**, 397 (1881).

[c] Ann. Phys. Chem., **12**, 526 (1881).

[d] Proc. Roy. Soc. London, **78**, Ser. A, 9 (1906).

[e] Proc. Roy. Soc. London, **77**, Ser. A, 292 (1906).

RATE OF ABSORPTION.

DETERMINING FACTORS.

The rate at which a solid absorbs a vapor depends upon several factors. These will be discussed in the following paragraphs.

Chemical composition.

In general, the chemical composition of the solid affects absorption to the extent that acid bodies tend to absorb basic vapors, and conversely. The magnitude of this influence varies from very pronounced chemical reaction, such as the fixation of gaseous ammonia by solid acids to extremely weak acid or basic effects.

Physical condition.

The physical condition of the solid, its fineness of division, determines the surface available for the purely adsorption effect, which, with other conditions the same, is directly proportioned to the surface of the solid in contact with the vapor. As the solid is reduced to finer powder the number of solid angles between the granules is increased, as well as the surface of solid exposed, and the condensed vapor retained in these solid angles is added to that held by simple absorption.

Viscosity of the vapor.

In the case of vapor entering a soil at rest there is a damping term due to the viscosity of the vapor. After taking account of the probable diameter of the capillary spaces through which the vapor is to pass, the resistance which the vapor offers to being forced into the soil is the viscosity of the vapor multiplied by its rate of flow,[a] and this rate of flow is the rate at which absorption is taking place. The diameters of the capillary spaces, too, become less as the surface of each grain takes on moisture, so the resistance to the passage of vapor increases as the absorption proceeds. Consequently we should expect rate curves for soils to show a decrease in rate of absorption with time greater than that for absorption of vapor upon a plane surface, but this factor has been found to be of only minor import.

Absorption capacity.

The absorption capacity of the solid affects the rate of absorption to a marked degree. Where the absorption capacity is high, the speed of absorption is very great.

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[a] See E. Wollny, Forsch. Agr.-Phys. **16**, 193 (1893); Buckingham, Bul. No. 25, Bureau of Soils, U. S. Dept. Agr. (1904).

Partial pressure, or humidity.

The rate of absorption of water by soils varies for atmospheres of different humidity in a manner similar to the change in rate of evaporation under different degrees of humidity, as can be seen from the curves in figure 15 for Sea Island cotton soil plotted from the data given in the lower half of Table IV. Ordinates are in percentage of moisture in the soil, abscissas are in time in days. All the experiments begin at 4.4 per cent of moisture, the quantity retained by Sea Island cotton soil in air-dry condition.

Van Bemmelen,[a] Hellriegel,[b] Puchner,[c] and von Dobeneck [d] have determined the speed with which a soil absorbs water vapor.

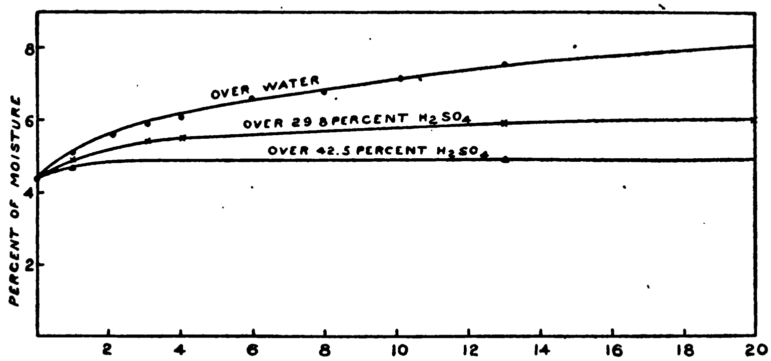

FIG. 15.—Curves showing rate of absorption of water vapor by Sea Island cotton soil under different degrees of humidity.

They, too, give very regular rate curves, but these, as well as Parks [e] rate of absorption of water vapor by glass wool, are likewise not described by a simple mathematical formula. Hantzsch [f] has shown that the rate of absorption of ammonia gas by solid organic acids in finely powdered condition depends upon the partial pressure of the ammonia gas in the atmosphere above the solid acid. Using absolute ammonia, the reaction is fairly well described by the first order reaction velocity equation, $K^{I.} = \frac{1}{t} \log.\left(\frac{a}{a-x}\right)$, and on dilution of the ammonia with air, this equation still holds if the total volume of gas employed is so great that the partial pressure of the ammonia is practically constant throughout the absorption process.

If, however, the quantity of ammonia present in the gas is considerably reduced by the absorption, then the rate of absorption is no longer expressed by this first order reaction velocity equation, but is more nearly given by the second order equation, $\mathrm{K}^{\mathrm{II.}} = \frac{1}{t} \frac{x}{(a-x)a}$. The same is true for the absorption of gaseous hydrogen chloride by solid organic bases. A similar effect is produced in the rate of absorption of water vapor by a soil as the atmospheric humidity varies.

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[a] Arch. Néer. (2), **10,** 267 (1906).

[b] Forsch. Agr.-Phys. **6,** 389 (1883).

[c] Land. Vers.-Stat., **46,** 229 (1895).

[d] Forsch. Agr.-Phys., **15,** 163 (1892).

[e] Phil. Mag. (6), **5,** 518 (1903).

[f] Zeit. phys. Chem., **48,** 289 (1904).

The rates of absorption of water vapor by humus from atmospheres saturated at different temperatures, as determined by von Dobeneck (Table XX), show, too, that the velocity of absorption is greater the higher the relative humidity.

The rate curves obtained from all of the foregoing tables are regular, but are not described by a simple velocity equation.

TABLE XX.—*Rate of absorption of water vapor by humus, according to von Dobeneck.*

Period.	Quantity of water absorbed at—						
	[a] 0° C.	[a] 10° C.	[a] 20° C.	[a] 30° C.	[b] 10° C.	[b] 20° C.	[b] 30° C.
Days.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	0.12	1.40	1.96	3.59	1.35	1.61	2.14
2	.50	2.47	3.22	6.27	2.22	2.48	2.29
3	.88	3.61	4.84	8.13	3.24	2.99	2.32
4	1.25	4.57	5.77	10.03	4.37	3.47	2.36
5	1.79	5.44	7.11	11.17	5.28	3.63	2.39
6	2.28	6.19	8.33	12.39	6.17	3.77	2.43
7	2.79	7.01	9.36	13.61	6.76	3.92	2.42
8	3.30	8.11	10.18	14.20	7.28	4.01	2.45
9	3.76	8.76	10.88	14.65	7.61	4.08	2.49
10	4.23	9.34	11.39	15.34	7.91	4.13	2.48
12	5.06	9.65	12.51	15.98	8.32	4.15	....
14	5.95	10.37	13.32	....	8.49	....	....
16	6.89	11.13	14.03	....	8.60	....	....
18	7.60	12.02	14.64	....	8.63	....	....
20	8.32	12.83	15.02	....	....	....	....
22	9.09	13.62	15.28	....	....	....	....
24	9.90	14.20	15.56	....	....	....	....
26	10.61	14.70	15.86	....	....	....	....
28	11.22	15.03	15.89	....	....	....	....
30	11.83	15.38	....	....	....	....	....
32	12.43	15.68	....	....	....	....	....
34	12.96	15.95	....	....	....	....	....
36	13.48	....	....	....	....	....	....
38	13.99	....	....	....	....	....	....
40	14.46	....	....	....	....	....	....
42	14.89	....	....	....	....	....	....
44	15.25	....	....	....	....	....	....
46	15.59	....	....	....	....	....	....
48	15.79	....	....	....	....	....	....
50	15.90	....	....	....	....	....	....

[a] Atmosphere saturated with moisture at temperature given.
[b] Atmosphere saturated with moisture at 0°.

Previously absorbed vapor.

As will be seen from the data on the rate of absorption of vapors by soils in Tables II, III, IV, V, VI, VIII, IX, X, and XI, the rate of absorption decreases as more and more vapor is held by the soil. This effect is only what would be expected when we remember that the last portions of vapor absorbed and condensed to liquid form exist to a considerable extent in the capillary spaces of the soil as well as in the form of films upon the surface of the soil grains.

Temperature.

(*a*) It has been shown by the investigations cited above and by the new experiments given in the section on the effect of temperature upon absorption, that in saturated atmospheres, at least, an increase in temperature decreases the mass of vapor absorbed by a solid. (*b*) Increase in temperature increases the mass of vapor which a given volume of air can hold at any one pressure. Theoretically, then, the first temperature effect (*a*) should reduce the time required to saturate the absorbing solid with vapor; and the second effect (*b*) should likewise hasten the absorption by providing a higher absolute quantity of vapor in the atmosphere for the solid to draw upon. This conclusion is borne out experimentally by the results obtained with Sea Island cotton soil; at 100° C. only one week was required for this soil to absorb all the vapor it could take up, whereas at 25° C. this same soil stood ninety-seven days over water before it ceased to absorb moisture. Von Dobeneck[a] confirms this effect of temperature upon rate of absorption as shown in Tables VII and XX.

Joulin[b] found that the time required to saturate charcoal with carbon dioxide decreased with increasing temperature at a constant pressure.

RATE OF EVAPORATION.

In a former bulletin the mechanism of evaporation has been discussed in considerable detail.[c] In addition to the data on the evaporation of moisture from soils under various degrees of humidity, which have been given in Tables II, III, and IV, above, we repeat here in Tables XXI, XXII, XXIII, and XXIV the data in that bulletin on the rate of evaporation from wet soils over concentrated sulphuric acid at 25° C. The point brought out by the evaporation data in all of these tables is that the rate of evaporation from any wet soil is fairly constant until the quantity of moisture still remaining in the soil is approximately that known as the "optimum water content" of the soil. At this point a gradual change in the rate of evaporation takes place, as shown in figures 16, 17, 18, and 19, which represent graphically the rate of evaporation indicated in Tables XXI, XXII, XXIII, and XXIV. Referring back to figures 1, 2,

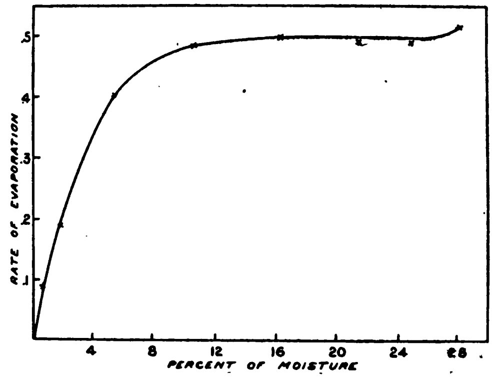

FIG. 16.—Curve showing rate of evaporation of water from Podunk soil.

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[a] Loc. cit.

[b] Comp. rend., 90, 741 (1880).

[c] Cameron and Gallagher, Bul. 50, Bureau of Soils, U. S. Dept. Agr., 1907.

and 3 we see this same bend in the rate of evaporation curves, which becomes less and less evident as the humidity of the atmosphere of the soil approaches the saturation point, going from the partial pressure of water vapor of 94 per cent sulphuric acid up to that of the vapor pressure of water alone. As was stated in Bulletin 50, the moisture content of each of these soils at which this bend in the rate of evaporation takes place is in reality very close to the content of water in the soil which gives it the best physical condition for plant growth.

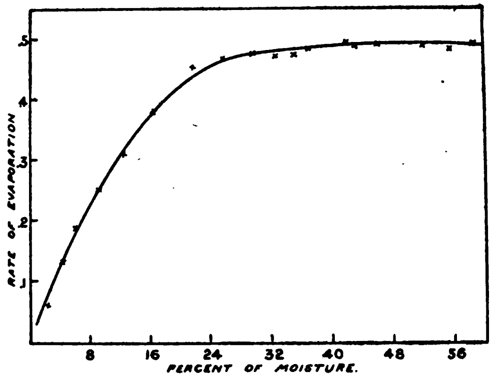

FIG. 17.—Curve showing rate of evaporation of water from Miami soil.

The reason for this agreement between the point at which the rate of evaporation changes and the point known as the "optimum water content" has been also pointed out in Bulletin 50. The larger open spaces between the soil grains naturally lose their water first, and the later portions of water evaporate more and more from the finer capillary spaces in the soil. When the water content of the soil is reduced to such a degree that the loosely held water in these more open spaces must draw upon the water held as a capillary film upon the soil grains, then very naturally evaporation proceeds more slowly, since the films are held by the soil grains quite tenaciously. At this same moisture content, too, where the pull of the capillary films of water upon the soil grains is brought into evidence, we would naturally expect that the very fine soil particles might be rearranged into larger aggregates and thus furnish a more open structure better suited for access of atmospheric gases and for the penetration of roots.

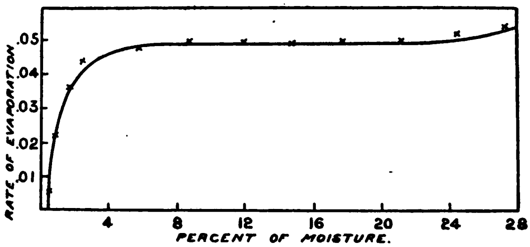

FIG. 18.—Curve showing rate of evaporation of water from Leonardtown soil.

In this connection it is interesting to note that Heinrich[a] has shown that the quantity of water in a soil required for plant growth is always greater than the quantity of water the soil can take up from a saturated atmosphere. A heavy soil containing a high percentage of moisture may hold the water so absorbed that while the plant can get some water, still it is by no means fully supplied.

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[a] Zweiter Ber. landw. Vers.-Stat. Rostock, p. 19 (1894): E. S. R., **7**, 481 (1895–96). See also Spalding, Bot. Gaz. **38**, 122 (1904).

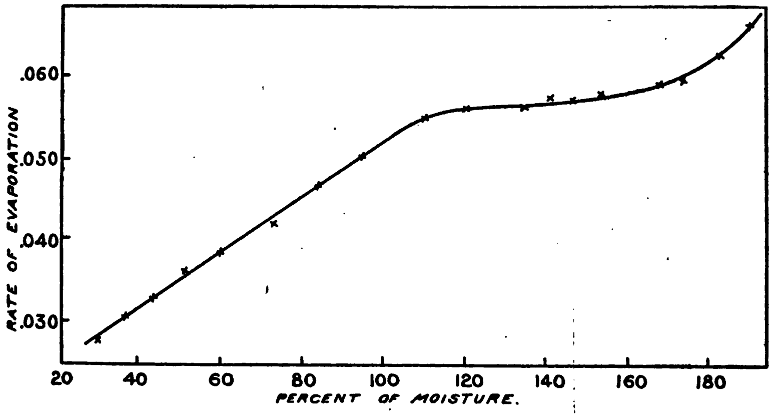

FIG. 19.—Curve showing rate of evaporation of water from muck soil.

TABLE XXI.—*Rate of evaporation from Podunk fine sandy loam over 95 per cent sulphuric acid at 25° C., according to Cameron and Gallagher.*

Mean moisture content.	Period.	Loss of moisture.	Loss per hour.
Per cent.	*Hours.*	*Grams.*	*Grams.*
27.4	19.5	1.0450	0.0563
24.2	4.5	.2362	.0525
21.3	18.7	.9210	.0493
17.8	9.3	.4595	.0494
14.8	15.3	.7495	.0490
12.0	9.9	.4854	.0490
8.7	14.5	.7140	.0492
5.8	9.9	.4712	.0476
2.4	4.0	.1732	.0433
1.7	2.0	.0719	.0359
0.9	11.0	.2445	.0222
0.3	2.0	.0097	.0049

TABLE XXII.—*Rate of evaporation from Miami black loam over 95 per cent sulphuric acid at 25° C., according to Cameron and Gallagher.*

Mean moisture content.	Period.	Loss of moisture.	Loss per hour.
Per cent.	*Hours.*	*Grams.*	*Grams.*
58.5	16.70	0.8198	0.0491
55.4	9.30	.4474	.0481
52.4	15.17	.7422	.0489
49.4	9.90	.4802	.0485
46.4	14.50	.7155	.0493
43.4	9.90	.4808	.0486
41.0	11.00	.5427	.0492
37.5	11.00	.5411	.0483
35.4	6.50	.3099	.0477
32.6	17.50	.8295	.0474
29.7	7.00	.3321	.0474
26.9	17.00	.7964	.0468
22.1	24.00	1.0879	.0453
17.1	24.00	.9109	.0379
12.9	26.25	.8108	.0309
9.5	22.25	.5716	.0257
6.7	24.50	.4694	.0192
5.1	22.75	.3056	.0134
3.7	23.75	.2136	.0090
2.7	24.25	.1470	.0061

TABLE XXIII.—*Rate of evaporation from Leonardtown loam over 95 per cent sulphuric acid at 25° C., according to Cameron and Gallagher.*

Mean moisture content.	Period.	Loss of moisture.	Loss per hour.
Per cent.	*Hours.*	*Grams.*	*Grams.*
28.2	19.00	0.9770	0.0517
24.9	7.25	.3555	.0490
21.6	19.25	.9538	.0495
16.4	22.00	1.0962	.0498
10.7	24.50	1.1963	.0488
5.5	22.75	.9193	.0404
2.0	24.25	.4560	.0188
.7	24.16	.0904	.0037

TABLE XXIV.—*Rate of evaporation from muck over 95 per cent sulphuric acid, at 25° C., according to Cameron and Gallagher.*

Mean moisture content.	Period.	Loss of moisture.	Loss per hour.
Per cent.	*Hours.*	*Grams.*	*Grams.*
190	9.50	0.6362	0.0669
183	15.20	.9590	.0632
174	9.85	.5905	.0600
168	14.50	.8639	.0596
154	10.60	.5813	.0581
147	13.00	.7474	.0575
141	6.50	.3744	.0576
135	17.50	.9893	.0566
121	17.00	.9591	.0564
110	24.00	1.3233	.0551
95	24.00	1.2120	.0505
84	26.30	1.2332	.0469
74	22.10	.9329	.0423
60	24.30	.9388	.0387
52	23.00	.8352	.0363
44	24.00	.7958	.0331
37	24.00	.7372	.0307
30	24.50	.6851	.0279

ENERGY CHANGES.

Poggendorff attributes the first experimental work on capillarity to Leonardo da Vinci, 1452–1519. A number of investigators[a] worked in the field before it was discovered that capillary phenomena are accompanied by heat effects. De Saussure[b] during 1812 to 1814 found that heat was evolved during the process of absorption.

Pouillet[c] showed the rise in temperature of various powders and porous substances when moistened with a liquid. Unfortunately, he, as well as several investigators following him, neglected to communicate the weight of powder and of liquid used and their specific heats; so we are unable to calculate the quantity of heat set free. He gives merely the rise in temperature produced by adding liquid to the material, using water, oil, alcohol, and ethyl acetate with finely divided metals, metallic oxides, powdered glass, clay, and other substances, including a number of organic solids. Water added to inorganic solids gave a rise of 0.2° to 0.6° C., while with dried organic material the temperature rise sometimes reached 10° C.

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[a] Ann. Phys. (Gilbert's), **47,** 113 (1814).

[b] For a more extended survey of the literature see Trans. Am. Electrochem. Soc., **11,** 387 (1907).

[c] Ann. Chim. Phys., **20,** 141 (1822); Ann. Phys., **73,** 356 (1823).

Ammon[a] cites the observations of Von Babo[b] on the rise in temperature experienced by dry soils when subjected to an atmosphere saturated with water vapor. These experiments are qualitative only, but they show the existence of the heat effect due to moistening a powder; that it is positive, and that the temperature rise is greater with soils containing humus than without.

Stellwagg[c] found a marked increase in the temperature on moistening various soils and soil constituents with water and on subjecting them to humid atmospheres. But he has given no data enabling us to calculate the number of calories liberated during this adsorption; consequently his data have only qualitative value. He concludes: (1) That the rise in temperature which the soil experiences upon addition of water, in general is greater the drier the soil, the finer its grains, and the lower the prevailing temperature. (2) That the rise of soil temperature on addition of water to a perfectly dry soil is very considerable (8.33° C. for a calcareous sand rich in humus, 6.6° C. for ferric hydroxide, 5.57° C. for a loam soil). (3) That when water vapor is adsorbed by soil constituents a temperature rise is observed as follows: Quartz sand, 0.00–0.25 mm. diameter, 0.88°; quartz powder, 1.08°; precipitated calcium carbonate, 1.47°; kaolin, 2.63°; ferric hydroxide, 9.30°; peat, 12.25° C. (4) That the temperature rise due to adsorption of dry carbon dioxide by dry soil constituents is inconsiderable, with the exception of ferric hydroxide, in which case the rise is 6.9° C., while the moist gas is adsorbed with a much greater temperature increase. (5) That dry soil constituents adsorb dry ammonia and experience a considerable temperature rise: Quartz powder, 0.80°; precipitated calcium carbonate, 0.80°; kaolin, 2.05°; ferric hydroxide, 18.05°; peat, 28.3° C. Moist ammonia shows less temperature rise; for ferric hydroxide and for peat it is, respectively, 14.1° and 23.80° C.

This heat evolved when a vapor condenses upon a solid absorbent was very naturally attributed to the latent heat of vaporization which became available on liquefaction. But Favre[d] found the heat liberated by absorption to be greatly in excess of the latent heat of vaporization, for three different gases; consequently, this assumption had to be abandoned. More recently Dewar[e] has shown that hydrogen, whose latent heat of vaporization at its boiling point is 120 gram calories, gives off six times that quantity of heat when absorbed by charcoal at the boiling point of air. Similarly, oxygen gas when absorbed by charcoal liberates twice the heat due to liquefaction.

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[a] Forsch. Agr.-Phys., **2**, 21 (1879).

[b] Mülder, Chemie der Ackerkrume, Band 3, p. 366.

[c] Forsch. Agr.-Phys., **5**, 211 (1882).

[d] Lehmann, Molecular-Physik. I, p. 85.

[e] Chem. News, **94**, 174 (1906); Proc. Roy. Soc., **74**, 130 (1904).

The experiments of Parks [a] indicate that the quantity of water absorbed by a powder from water vapor is very nearly the same as the quantity of water held on the surface of the grains when the powder is immersed in liquid water. He has shown that a silica powder saturated with water vapor gives off no measurable heat when brought into contact with liquid water, whereas the dry silica liberates a definite quantity of heat per square centimeter of surface, and this heat evolution decreases in a perfectly regular manner as the silica powder contains more and more absorbed water vapor.

Masson [b] has shown that the heat evolved when cotton absorbs water vapor is for practical purposes directly proportional to the quantity of moisture absorbed and is very nearly the same as the latent heat of vaporization. He finds the absorption by cotton to be much greater than is warranted by its area as compared with similar experiments using glass wool, and suggests as an explanation that the water absorbed penetrates into the cotton fiber as a solid solution. The thermal effect dealt with here is evidently different from that studied by Parks.[c]

When a gas is absorbed by a metal many interesting physical changes in the metal may be effected. Its volume, hardness, elasticity, electrical conductivity, and single potential and rate of solution in various solvent liquids are changed. The absorption of a gas, too, may depend upon its condition; that is to say, the energy it possesses. For example, free hydrogen gas is very slightly absorbed by iron and some other metals, but hydrogen freshly liberated from combination either by electrolysis or by action of metal upon acid is very strongly absorbed by iron. Palladium, on the other hand, absorbs free hydrogen with great avidity.

SUMMARY.

In the absorption of water vapor by quartz flour, a soil separate, and typical soils, the rate of approach to equilibrium between soil and water vapor has been followed at various degrees of humidity, and these equilibrium points determined.

The amount of water absorbed increases with the humidity, but not in a simple mathematical relation.

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[a] Phil. Mag. (6), **5**, 521 (1903).

[b] Proc. Roy. Soc. London, **74**, 249 (1904–5).

[c] Loc. cit.

Toluene and other vapors were compared with water vapor, using the same soils, and show in general an absorption of the same order of magnitude.

The velocity of absorption decreases regularly as absorption proceeds, but it is not described by a simple logarithmic equation.

Relatively small decrease in vapor pressure produces a marked increase in the rate at which the soil dries out. At the moisture content known as "optimum" for plant growth, a rapid decrease in the rate of evaporation takes place, and at this particular moisture content there are likewise changes in other physical characteristics of the soil, such as specific volume, resistance to penetration, etc., which altogether point strongly to a purely physical reason for the existence of a narrow range of water content in a soil at which plants thrive best.[a]

The content of water in a soil at which plants begin to wilt is greater than the quantity of water the soil can take up from a saturated atmosphere. A heavy soil containing a high per cent of moisture may hold the water so absorbed that while the plant can get some water still it is by no means fully supplied.

The absorptive capacity of soil for water vapor is generally higher the finer the texture of the soil and the greater the content of humus. In general, productive soils have a very considerable capacity for water vapor.

Gases are absorbed to a different degree by each solid substance; the different soil components all possess a considerable absorption capacity, and mixtures of these constituents absorb gases additively; that is, each soil material exerts its absorptive effect independently of the rest of the soil about it. Soil constituents moistened with water absorb gases in greater quantity than would the same mass of water alone. Easily condensed gases are in general absorbed more easily.

Heat is evolved during the process of absorption, and this heat is greatly in excess of that given out by the condensation of the vapor to a liquid.

For equilibria between soils and atmosphere saturated with water vapor over a temperature range from 25° C. to 100° C., the amount of water absorbed decreases with increasing temperature. This confirms the results obtained by earlier investigators for the absorption of water vapor as well as for gases in general.

Absorbed gases are held with remarkable tenacity. Glass and minerals retain hygroscopic water up to 500° to 800° C.

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[a] See Cameron and Gallagher. Bul. 50, Bureau of Soils, U. S. Dept. of Agr., 1907.

Bodies which have been heated and then cooled in a vacuum show high absorptive power; consequently, absorption can not be looked upon solely as the solution of a gas in moisture films upon the grains of the solid.

In general, nitrogen is absorbed by soils in greater quantity than oxygen. This is especially interesting, since the absorption of oxygen and nitrogen from air by water gives a higher ratio of oxygen to nitrogen in the solution than the 1:4 relation which exists in air. The similar high absorptive power of aluminum hydroxide, ferric hydroxide, and magnesium carbonate for nitrogen indicates that this preference of soils for nitrogen is a real phenomenon, since these substances have no way of masking their true absorptive power for oxygen by converting it chemically to carbon dioxide, as a soil does, or to other oxides.

The absorption of carbon dioxide by soils is due in great measure to the presence of hydrated oxides, such as ferric oxide, and humus. Kaolin, calcium carbonate, and quartz also absorb carbon dioxide, but in comparatively small amounts.

Soils, whether acid or alkaline, dry or wet, absorb ammonia from the atmosphere in appreciable amount.

No one mathematical expression has been found to hold generally for the distribution of a gas between the vapor phase and absorbing solid. The specific attraction of solid and gas, the diffusion of gas into solid, the condensation of gas to liquids and consequent clogging of capillary channels where the forms and arrangement of these minute spaces enter to determine the vapor pressure of the liquid there enmeshed, all these factors complicate the observed relation of mass of gas adsorbed to mass of gas left in the vapor phase.

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